Assessment of paleo-depositional environments and reservoir potential of the Late Cretaceous North Cape Formation, Nelson, New Zealand.

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by

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Frontispiece:

View of the central Whanganui Inlet from Knuckle Hill, Kahurangu National Park.

Abstract:

The Taranaki Basin contains New Zealand's only producing hydrocarbon systems with commercial production limited to Paleocene, Eocene, Oligocene Miocene to latest Pliocene successions. Potential hydrocarbon reservoirs have been identified in Late Cretaceous successions within the Pakawau Sub-basin of within the southern region of the Taranaki Basin. The lowermost Rakopi Formation has been identified as both a hydrocarbon source and a potential reservoir, while the less well understood North Cape Formation is thought to represent a more unconventional petroleum play in that it contains both reservoir and a disseminated hydrocarbon source. Despite their economic significance the Late Cretaceous potential sandstone reservoirs are not well defined.

In this study, highly detailed stratigraphic sections were constructed from selected outcrops of the North Cape Formation with sedimentary analyses revealing obvious lateral variation in the lithofacies. The North Cape Formation is interpreted to have been deposited in a tidally dominated, sandy estuarine setting. There is a distinct change in average grain size across the field area, with the northeastern region characterised by medium sandstones and conglomerates, while the central, southern and western regions are dominated by fine sandstones. An active bay head fan delta dominated deposition in the northeast of the field area and partially sheltered tidal embayments and local salt marshes separated by smaller scale tidal distributary channels characterise the central regions of the study area. There is a marked reduction in the occurrence of tidal signatures in the uppermost North Cape Formation successions, marking a change from delta front to delta plain dominated deposition. The outcropping North Cape Formation and the framework for the characterisation of paleoenvironments presented in this study can be used as analogues for similar estuarine succession in the geological record.

Lithofacies and petrophysical analyses indicate the North Cape Formation contains viable hydrocarbon reservoirs. Porosity and permeability measurements assign the best quality reservoirs to conglomerate, wavy and crossbedded sandstone lithofacies, with moderate quality reservoirs identified in both the heterolithic and planar laminated sandstone lithofacies. A number of organic rich sandstone, siltstone and freshwater and salt water influenced coal lithofacies have also been identified which may represent potential source rock units. Gamma Ray profiles confirm the onshore North Cape Formation is dominated by sandstone, with less interbedded siltstones and coal beds than the underlying Rakopi Formation.

This work suggests that future exploration within the North Cape Formation may regard the formation as both a potential reservoir and source rock interval.

Acknowledgements

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Chapter 1 - Introduction

1.1 – Introduction:

Late Cretaceous rocks contained within New Zealand's Taranaki Basin represent the most productive hydrocarbon source rocks of the region (King and Thrasher, 1996; Higgs et al., 2010). Although hydrocarbons having have not as of yet been produced from older Cretaceous units, many authors have described their reservoir potential with the aim of extending the prospectivity of what is an already established hydrocarbon province (Knox, 1982; Wizevich et al., 1992; King and Thrasher, 1996; Browne et al., 2008; Higgs et al., 2010). Despite their economic significance the Late Cretaceous potential sandstone reservoirs are not well defined. Paleogeographic reconstructions and the interpretation of petroleum potential are largely based on seismic mapping and limited outcrop analysis with very few well penetrations (King and Thrasher, 1996; Browne et al., 2008). Thorough facies analyses of onshore Late Cretaceous successions may provide useful depositional models for offshore production.

The Pakawau Sub-basin a 5000km^2 component depocentre of the much larger Taranaki Basin is a rift-related sub-basin in the southwestern portion of the Taranaki Basin (Bal and Lewis, 1994; Higgs et al., 2010). The sub-basin is filled with Pakawau Group sediments which comprise the oldest sedimentary rocks of the Taranaki Basin and lie unconformably over Cretaceous plutonic and Paleozoic metasedimentary basement rocks (Wizevich et al., 1992; Browne et al., 2008). The lower Rakopi Formation has been identified as both a hydrocarbon source and a potential reservoir, while the upper North Cape Formation may represent a unique target for both reservoir and a disseminated hydrocarbon source (Higgs et al., 2010). These sediments accumulated as thick and lithologically variable successions within normal fault-bounded graben over many parts of the Taranaki Basin and contain up to 4.2km thick Late Cretaceous successions in some parts of the Taranaki Basin (King and Thrasher, 1996; Higgs et al., 2010).

Uplifted Cretaceous-Cenozoic sediments of the Pakawau Sub-Basin outcrop in the onshore area of northwest Nelson around the shoreline and streams that flow into the Whanganui Inlet, where low tide provides access to good exposure in shore platform and steep sea cliffs outcrops (Bal, 1992; Wizevich, 1994; Stark, 1996). The importance of Late Cretaceous rocks as potential hydrocarbon reservoirs in the Taranaki Basin has been acknowledged, though few authors have described the lithofacies and outcrop relationships (Wizevich et al., 1992; Bal and Lewis, 1994; Wizevich, 1994; Stark, 1996; Browne et al., 2008; Higgs et al., 2010).The majority of these studies have considered the Late Cretaceous Rakopi Formation, with less of a focus on the latest-Cretaceous North Cape Formation. Previous investigations have formed the basis of understanding for the deposition of Late

Cretaceous rocks of the Pakawau Sub-Basin and have facilitated the high-detailed assessment of lithofacies and local paleogeographic changes across available outcrop in this study in order to inform depositional setting and the petroleum potential of the North Cape Formation within the Southern Taranaki Basin. It should be noted that currently there is no production of oil or gas from the North Cape Formation.

The purpose of this research is to describe and interpret in detail, stratigraphic units of the North Cape Formation in the onshore portion of the Pakawau Sub-Basin, in order to assess their potential as a petroleum reservoir facies. This research documents highly-detailed facies interpretations on available North Cape Formation outcrop within the Whanganui Inlet, NW Nelson. Sedimentological interpretation was carried out at a number of coastal and one near coastal outcrop around the inlet. These interpretations were used to establish the paleo-depositional environments, draw conclusions on the lateral lithofacies variations within the field area and along with petrophysical data guide interpretation for the potential of the heterolithic North Cape Formation as a hydrocarbon reservoir and/or hydrocarbon source within the Southern Taranaki Basin. Additionally these highly detailed analyses will be used to establish the relative significance of North Cape Formation sedimentation as an analogue for similar rift-basin settings in the Taranaki Basin.

1.2 – Regional geological history:

The Cretaceous Period marked an important time in New Zealand's geological history with a shift from prolonged convergent margin tectonics to widespread extension in eastern Gondwana (Laird and Bradshaw, 2004). The eastern region of Gondwana experienced subduction until the middle Cretaceous (c.105 Ma) when it underwent an abrupt shift to an extensional regime (Thrasher, 1992; Laird and Bradshaw, 2004; Strogen et al., 2017). This change was accompanied by significant uplift and erosion, producing a New Zealand wide angular unconformity. The extensional succession between 105-83 Ma manifested itself in the initiation of widespread rift sedimentary basins and subsequent deposition of both fluvial and marine sediments (Thrasher, 1992; Laird and Bradshaw, 2004; Mortimer, 2004; Strogen et al., 2017).

The Taranaki Basin formed during this rifting phase when the eastern margin of Gondwana was fragmenting to form the continent of Zealandia (Laird and Bradshaw, 2004; Mortimer, 2004; Mortimer et al., 2017) and the subsequent opening of the Tasman Sea. The current form of the Taranaki Basin is bounded in the east by the major Cretaceous reverse fault, the Taranaki Fault. The Taranaki Basin gradually shallows onto the bathymetric high of the Challenger Plateau to the southwest (Thrasher, 1992) and extends in a northwest direction into the New Caledonia Basin (Laird and Bradshaw, 2004; Strogen et al., 2017).

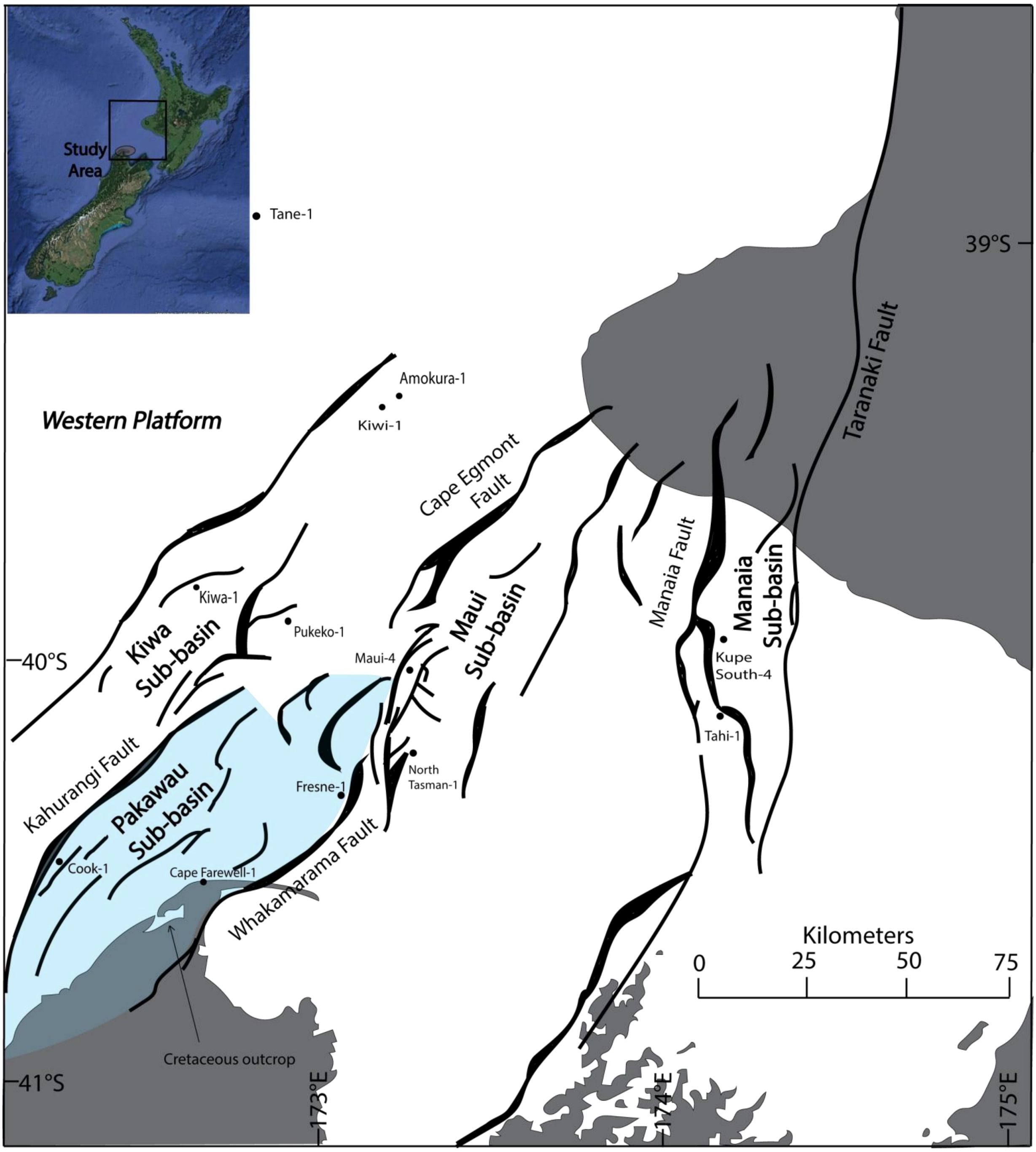


Figure 1.2 – Structural elements of the central and southern Taranaki Basin rift-related sub-basins, Cretaceous outcrop and locations of exploration wells mentioned in this study. Adapeted from (Higgs et al., 2010)

The predominantly offshore Taranaki Basin covers an area approximately 100,000km^2 and contains up to 8 km of Late Cretaceous and younger strata. A modern (since 1980's) and an extensive network of 2D seismic reflection lines that are tied to over 650 wells in the region with a growing number of 3D seismic volumes providing detail at a more local scale (Reilly et al., 2015). As such, publically available data (seismic and well) provide an excellent dataset to constrain the evolution of the New Zealand plate boundary from the Mesozoic break-up of Gondwana to the Cenozoic subduction of the Pacific Plate (Reilly et al., 2015).

Recent research suggests a two-fold evolution of the Taranaki Basin from the Cretaceous to Paleocene separated by a period of uplift, erosion and deposition. The initial rift phase in the evolution of the Taranaki Basin (c. 105-83Ma) has been established through identification of mid-Cretaceous rift basins in the greater Taranaki Region from modern seismic datasets. Two seismically mappable units facilitated a division of the syn-rift succession into the mainly terrestrial 'early syn-rift' and dominantly marine transgressive 'late syn-rift' (Strogen et al., 2017) which can be confidently correlated across much of the northern Taranaki and Deepwater Taranaki Basins. These basins are older and distinct from Late Cretaceous rift basins based on morphology.

A secondary period of rifting, the 'West-Coast-Taranaki rift phase', occurred during the latest Cretaceous and into the Paleocene (c. 80-55ma), producing additional normal faulting and local extensional sub-basins in the southern Taranaki Basin (Figure 2) (Reilly et al., 2015; Strogen et al., 2017). Normal faults associated with mid to-Late Cretaceous to Paleocene rifting strike along two dominant trends; one to the north and the other to the northeast (Thrasher, 1992; King and Thrasher, 1996; Reilly et al., 2015). North trending faults, more predominant in the central and northern areas of the basin, reflect Mesozoic terrane boundaries in basement rocks while the northeast-trending normal faults in the southern portion were mainly initiated during the mid to-Late Cretaceous rifting, with episodic reactivation during the Cenozoic (Figures 1, 2) (King and Thrasher, 1996; Reilly et al., 2015). Despite complex reactivation histories a number of the larger Late Cretaceous-Paleocene faults form the western margins of large half-grabens. The Late Cretaceous rocks of the Taranaki Basin were deposited in a number of these small en-echelon sub-basins with the greatest accumulations represented in the Pakawau, Manaia and Maui sub-basins in the southern Taranaki Basin and the Moa and Te Ranga sub-basins to the north (Thrasher, 1992; Higgs et al., 2010; Reilly et al., 2015).

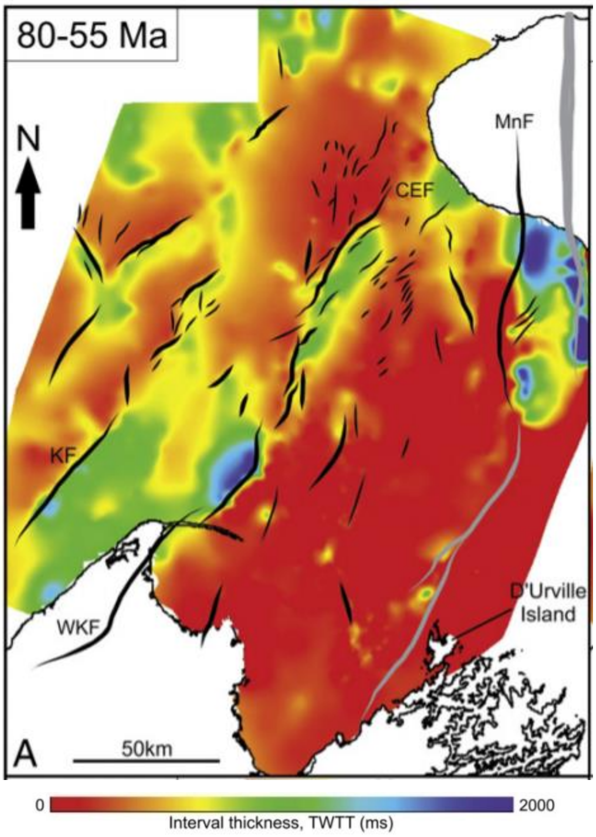


Figure 1.2 – Isopach map for the 80-55 Ma interval showing active normal (in black) and reverse faults (in grey) over the Late Cretaceous to Paleocene. Fault name abbreviations are as follows; WKF: Whakamarama Fault; CEF: Cape Egmont Fault; MnF: Manaia Fault; KF: Kahurangi Fault. Map after Reilly et al. (2015).

By the Late Oligocene the Southern Taranaki Basin had become a site of stable and quiet marine deposition, with sedimentary fill increasing in thickness toward the Taranaki Fault (Knox, 1982). Late Miocene subduction to the east of New Zealand produced a transpressional tectonic regime that lead to the inversion of a number of normal faults and the development of major anticlines in the southern Taranaki Basin (Bal, 1992). The subsequent uplift resulted in the exposure of the Late Cretaceous rift-related sedimentary fill in the Pakawau Sub-Basin (Knox, 1982; Bal and Lewis, 1994; King and Thrasher, 1996).

The Late Cretaceous initiated Pakawau Sub-Basin, the southern–most sub-basin formed in the Late Cretaceous, lies at the transition into the West Coast Basin-and-Range Province(Wizevich, 1994). Covering approximately 5000km² the Pakawau Sub-Basin trends north-east and is bounded by the Kahurangi Fault in the north-west and Whakamarama Fault in the east (Figure 1) (Thrasher, 1992; Bal and Lewis, 1994; Stark, 1996). The northern limits of the basin are poorly defined, while to the south the sub-basin terminates where the Late Cretaceous rocks onlap onto basement rocks, predominantly the Western Province metasedimentary and Karamea suite granites (Bal and Lewis, 1994; Mortimer, 2004). The dominant structural feature of the onshore portion of the sub-basin is the northeast-plunging asymmetric Whakamarama anticline, formed by the reverse reactivation of the Whakamarama Fault during the Late Miocene (Thrasher, 1992). Outcrops dip at gentle angles within the Whanganui Inlet (10-20° to the northwest) and more steeply in the Puponga area to the north (15-25°) to the northwest (Bussell, 1985; Bal and Lewis, 1994; Stark, 1996) (Figure 3).

1.3 – The Taranaki Basin petroleum systems:

The Taranaki Basin is New Zealand's only productive hydrocarbon region, with commercial production from Eocene paralic and terrestrial sandstones, and Miocene-latest Pliocene shelf sandstones (Robinson and King, 1988). Initial paleogeographic reconstructions produced from 1980's well data by Robinson and King (1988) highlighted potential sandstone reservoir maps for the Cretaceous-Paleocene sequences. Important potential reservoirs are interpreted to occur within the variable thickness non-marine to marginal marine quartzoze conglomerates, sandstones and mudstones of the Late Cretaceous Pakawau Group (Collen and Newman, 1991; Browne et al., 2008; Higgs et al., 2010).

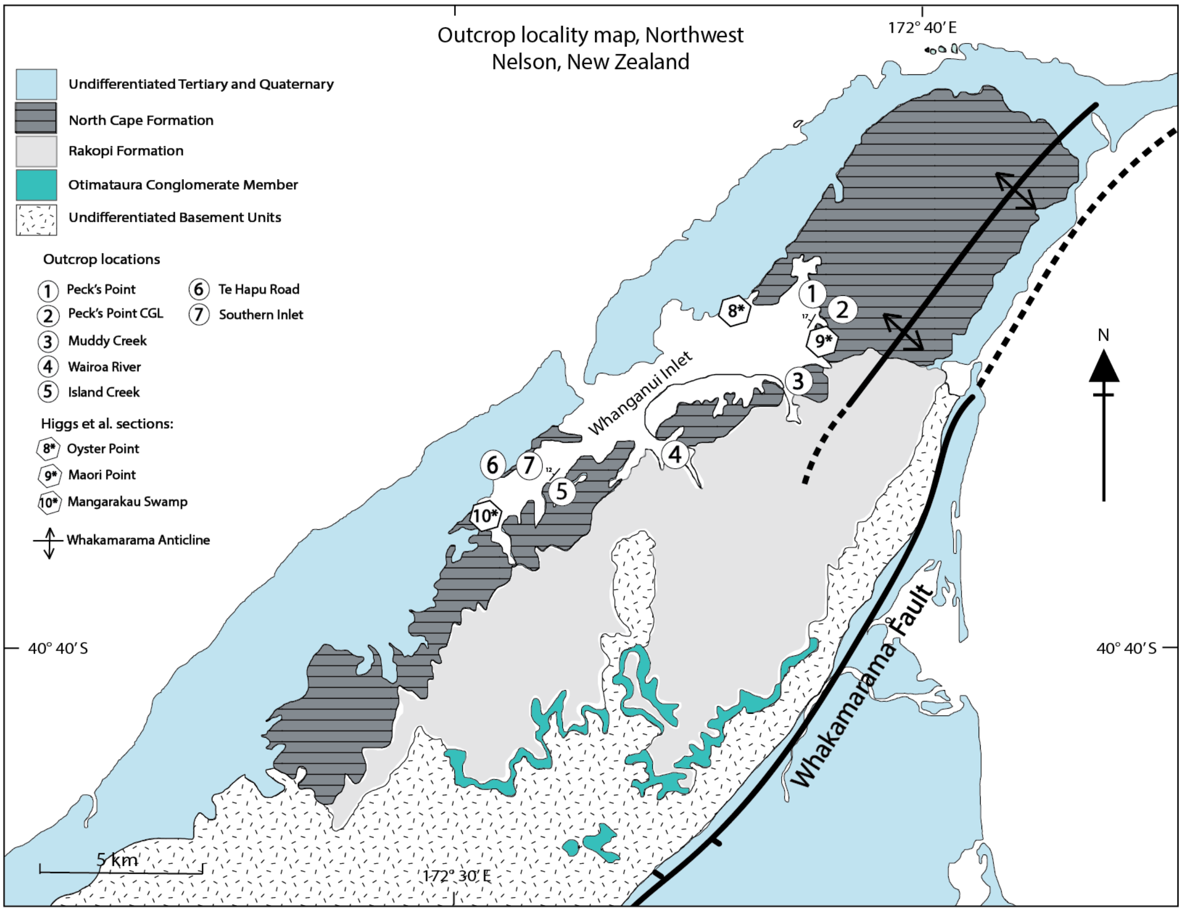


Figure 1.3 – Geology and structural elements of the onshore Pakawau Sub-basin, NW Nelson. Outcrop localities used in this research are denoted by numbers, * refers to those published in Higgs et al. (2010)

In the onshore portions of the Taranaki Basin the burial depths of Late Cretaceous units exceed 5km, and as this is where the predominant exploration has taken place results in sparse data sets and limited understanding of their potential as petroleum reservoirs. Within the offshore areas of the basin Cretaceous strata have typically not reach as considerable burial depths, instead occurring at present depths of 1-5km, while in the southernmost extent of the basin these strata are exposed onshore NW Nelson (Higgs et al., 2010).

Late Cretaceous successions have been penetrated by 16 open-file petroleum wells within the offshore Taranaki Basin and by a single onshore well (Cape Farewell-1) in NW Nelson. These wells mostly pre-date 1990, though recent interest in Cretaceous petroleum plays has seen new wells on the Western Platform target Cretaceous strata (e.g. Takapu-1 by STOS in 2004 and Hoki-1 drilled by AWE in 2010) (Higgs et al., 2010). The southern portion of the Taranaki Basin has the thickest accumulations of Late Cretaceous strata, and well TD has reached these sequences (Cape Farewell-1, Cook-1, Fresne-1, Kupe South-1, Pukeko-1, Tahi-1). Wells drilled into thick Late Cretaceous strata within the Pakawau sub-basin are the Cook-1 and Cape Farewell-1, with the latter onshore and in relatively close proximity to the only outcropping units of Late Cretaceous strata. Correlation of these sequences across the Taranaki Basin is difficult, due to similar biostratigraphic characters of both the Rakopi and North Cape Formations, considerable distances between wells used for calibration in seismic mapping and the significant variation in thickness of Late Cretaceous strata due to local basement relief (Robinson and King, 1988; Higgs et al., 2010).

Many studies suggest that the main hydrocarbon sources within at least the southern and central Taranaki Basin are coals within the Late Cretaceous Pakawau and deeper Eocene Kapuni Group rocks (Collen and Newman, 1991; King and Thrasher, 1996). The coal bearing Rakopi Formations is a proven source and indicated as a potential reservoir and it is likely the channel sandstones and higher energy shoreface sandstones of the North Cape Formation may also represent suitable reservoir rock, while local disseminated coals and organic rich units may provide a more unconventional petroleum play (Higgs et al., 2010).

1.4 – The Pakawau Group sedimentary units:

Pakawau Group rocks represent the Late Cretaceous syn-rift strata that are widely distributed throughout the Taranaki Basin, outcropping onshore to the northwest of Nelson (Knox, 1982; Browne et al., 2008). Early investigation into the Pakawau Sub-basin was driven by the assessment of the economic potential of the coal bearing units exposed within the basin. The investigations by Forbes , F. Von Hochstetter, Von Haast, Hector and Von Ettinghousen formed the basis for the definition of the region's geology and mineral resources (Ongley and MacPherson, 1923). A synthesis of the development of the stratigraphic nomenclature for the Pakawau Sub-basin is shown in (Table 1.1)

The onshore strata of the Pakawau Sub-basin were first formally subdivided by Ongley and MacPherson (1923) where, due to an apparent hiatus in sedimentation, two series were established: 1) the lower (eastern) coal-bearing Pakawau Series, and 2) the overlying (including 'brown' coal seams) Westhaven Series. Subsequent revision redefined this to the Pakawau Group to include the Westhaven Series, distinguishing the upper portion of the Pakawau Group into the Farewell, Wharariki, Puponga and North Cape Formations (youngest to oldest) Suggate (1956). These units span from Cretaceous to Eocene and were all interpreted as terrestrial deposits. The lower portion of the Pakawau Group remained undifferentiated until 1971, when it was reclassified into three formations; The basal Otimataura Conglomerate, the overlying undifferentiated Pakawau Group and the laterally discontinuous coal bearing Puponga Formation (Bishop, 1971). This research also established the localised nature of both the Puponga Formation and the basal conglomerate unit.

Titheridge (1977) differentiated the Upper Pakawau Group, proposing a consolidation of the Wharariki Formation into the Farewell Formation. He interpreted the depositional setting of the Upper Pakawau Group rocks as entirely non-marine, accumulating in a rapidly subsiding depression. It was concluded that braided stream sedimentation dominated the North Cape and Farewell Formation deposition and floodplain sedimentation was the depositional mode for the discontinuous Puponga Formation. Paleocurrent analysis established sediment transport occurred from the south and east (Titheridge, 1977).

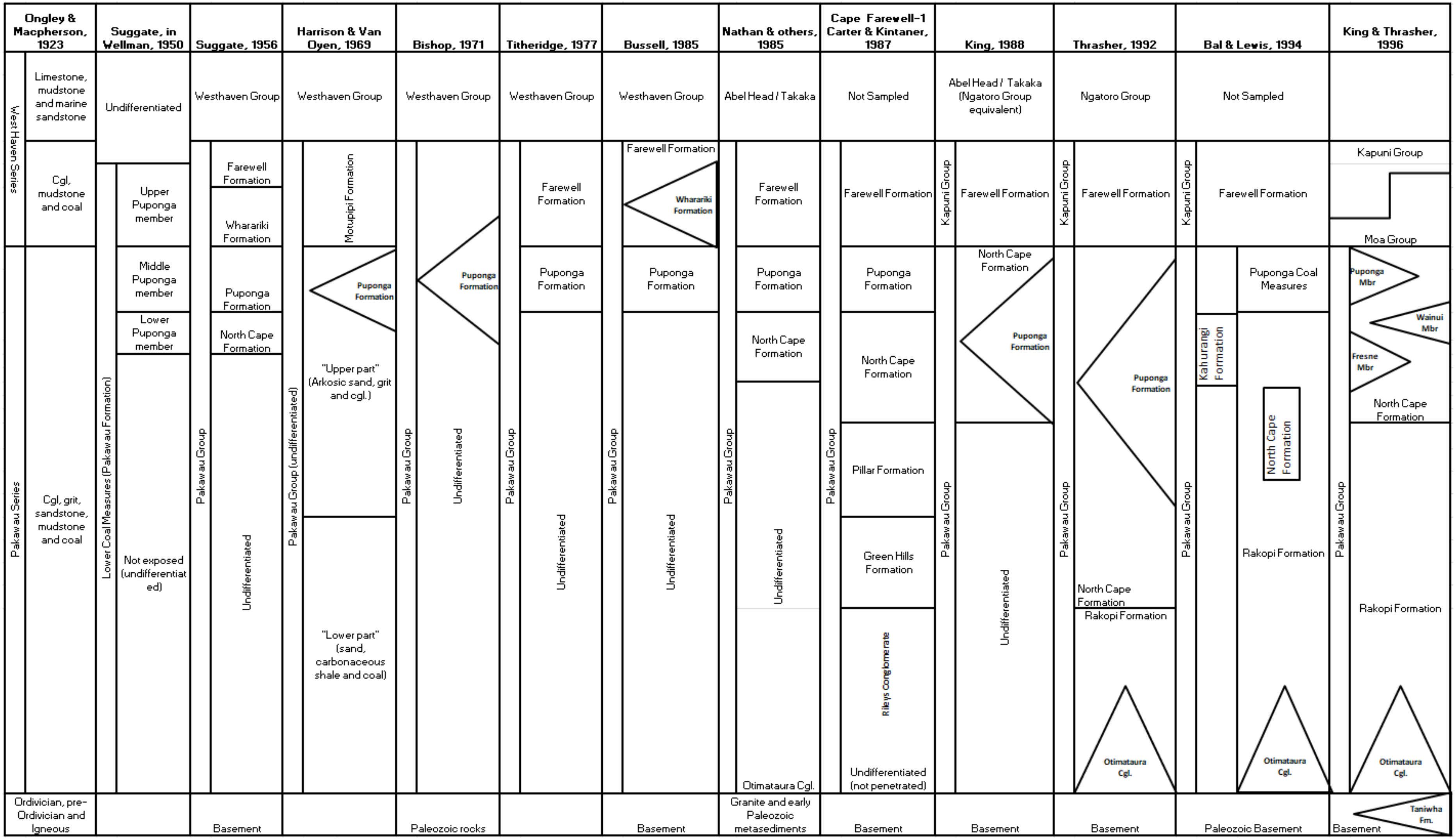
Significant interest in coal production in the 1980's resulted in a series of unpublished reports that presented detailed mapping and assessment of the coal bearing strata of the Pakawau Group. These detailed investigations of local strike trends enabled the correlation of coal bearing units in the southern (Mangarakau) region and the Puponga and upper North Cape Formations in the Puponga Coalfield (Bussell, 1985). As with previous investigation these reports also assigned entirely terrestrial sedimentation until the onshore exploration well Cape-Farewell 1 penetrated glauconitic rock which contained a single dinoflagellate (Carter and Kintanar, 1987). Seismostratigrpahic analysis of the onshore Pakawau Group suggested deposition was controlled by the formation of alluvial fans adjacent to the major faults. Basinward these alluvial fans gave way to braided river systems, until a reduced basin gradient resulted in meandering systems and associated swamp and lake sediments becoming prevalent, while the glauconitic sediments were concluded to have been deposited on a tidally-influenced coastal plain (Carter and Kintanar, 1987; King and Thrasher, 1996; Stark, 1996).

The summary of offshore Taranaki well sheets completed by King (1988) formalised the stratigraphic nomenclature for the Taranaki Basin sub-surface, which lead to the redefinition of the previous Pakawau Group nomenclature with the identification of a distinct seismic reflector separating the Farewell Formation overlying the North Cape into the Paleocene Kapuni Group (King and Thrasher, 1996). This reflector is suggested to coincide approximately with the K/T boundary. Thrasher (1992) noted the difficulty in applying this to the outcrop where the identification of the Cretaceous/Tertiary boundary was yet to be precisely located. This boundary has since been assigned to a distinct unconformity between marginal marine North Cape Formation and the quartzose-rich fluvial deposits of the Farewell Formation at Oyster Point (Higgs et al., 2010) and to outcrops near Melbourne Point and South Head described by Bal (1992) and Bal and Lewis (1994).

These studies combined biostratigraphic, seismostratigraphic and sedimentary analyses into a framework of depositional environment which ultimately indicated a Late Cretaceous marine transgression. More modern research adopts this nomenclature and has built on interpretation of marine transgression, where marine influence in Late Cretaceous rocks has been confirmed based on recognition of tidally-influenced structures first noted by Ongley and MacPherson (1923) and dinoflagellates from the North Cape Formation in the Whanganui Inlet, NW Nelson (Bal, 1992; Thrasher, 1992; Wizevich et al., 1992; Bal and Lewis, 1994; Stark, 1996).These outcrop interpretations were combined with seismic reflection mapping tied to offshore wells with known marine influence. Seismic interpretation clearly denotes a continuous upper Late Cretaceous stratigraphic sequence throughout the rift sub-basins, including the Pakawau Sub-basin, in the greater southern Taranaki Basin (Thrasher, 1992).

The most recent reconstruction of Late Cretaceous paleogeography presented in Strogen et al. (2011) shows marine transgression occurring from the Late Haumurian into the latest Haumurian, which controlled the depositional settings of the North Cape Formation until the early Teurian shift to fluvial-shallow marine deposition of the Paleocene Farewell Formation.

Table 1.1 – Development of the stratigraphic nomenclature for the Pakakawau Sub-basin.



The early development of the North Cape Formation in the Late Haumurian (c.68Ma) is shown in figure 3A, where marine flooding of much of the Taranaki Basin forms a shallow marine shelf with some non-marine strata, assigned to the Wainui Member, and intra-basinal highs on which deposition of Late Cretaceous strata was unlikely (King and Thrasher, 1996; Strogen et al., 2011). Coal bearing units of the lowermost North Cape Formation have been inferred from seismic and well data, spanning much of the central and western Taranaki Basin. Thin coal bodies reach as far as the western platform and to the Pakawau sub-basin in the south. Recognition of marine influenced strata in the Cook-1, Kiwa-1, Pukeko-1 and Maui-4 wells leads to the interpretation of marginal to shallow marine embayment that covered much of the Pakawau, Kiwa and Maui sub-basins.

Figure 3B depicts the latest Haumurian (c.66Ma) deposition of the North Cape Formation, where active normal faulting and marine transgression continued, covering much of the Taranaki Basin in shallow marine shelfal environments (Strogen et al., 2011). The coal bearing units of the lower North Cape Formation are capped by shallow marine strata, suggesting gradual inundation of the assumed coastal plain environment in the northern portions of the Taranaki Basin. Over this time marine-influenced sandstones were still being deposited in the Pakawau Sub-basin to the south

The nomenclature for the Late Cretaceous sedimentary fill of the Pakawau Sub-basin used in this study follows that proposed by King and Thrasher (1996) and the interpretations mentioned above. Pakawau Group is used for two distinct lithostratigraphic formations; 1) the lower Haumurian aged (c.75Ma) Rakopi Formation, an up to 1500m thick, coal bearing succession dominated by fluvial deposition but with some marine influence and 2); the latest Haumurian aged (c. 68-66Ma) North Cape Formation, also up to 1500m thick and a marginal marine unit, generally devoid of coal except in its expression within the Whanganui Inlet, NW Nelson (King and Thrasher, 1996; Stark, 1996; Browne et al., 2008; Strogen et al., 2011).

1.3.1 – North Cape Formation sedimentary interpretations:

Early investigations into the sedimentation of the North Cape Formation assign deposition to an entirely non-marine setting, where braided rivers were considered the dominant mode of deposition (Suggate, 1956; Bishop, 1971; Titheridge, 1977). More recent biostratigraphic, seismic and field analyses presented by Wizevich et al. (1992) and later by Thrasher (1992) and Higgs et al. (2010) suggest that much of the North Cape Formation has a strong marine influence. Thrasher (1992) suggests that by the latest Cretaceous the marine transgression was significant enough to result in at least the partial submergence of the Pakawau sub-basin, to form a shallow marine-embayment. He interprets the North Cape Formation as deposited in the resultant restricted marine, tidally influenced setting. It is locally enriched in coal and highly carbonaceous mudstones that were deposited in a setting interpreted to periodically fluctuate between coal swamp, fluvial and shallow marine following successive marine transgressions and regressions (Titheridge, 1977; Bal and Lewis, 1994; Stark, 1996; Browne, 2009; Higgs et al., 2010). The North Cape Formation becomes entirely marine towards the central and northern parts of the Taranaki Basin (King and Thrasher, 1996).

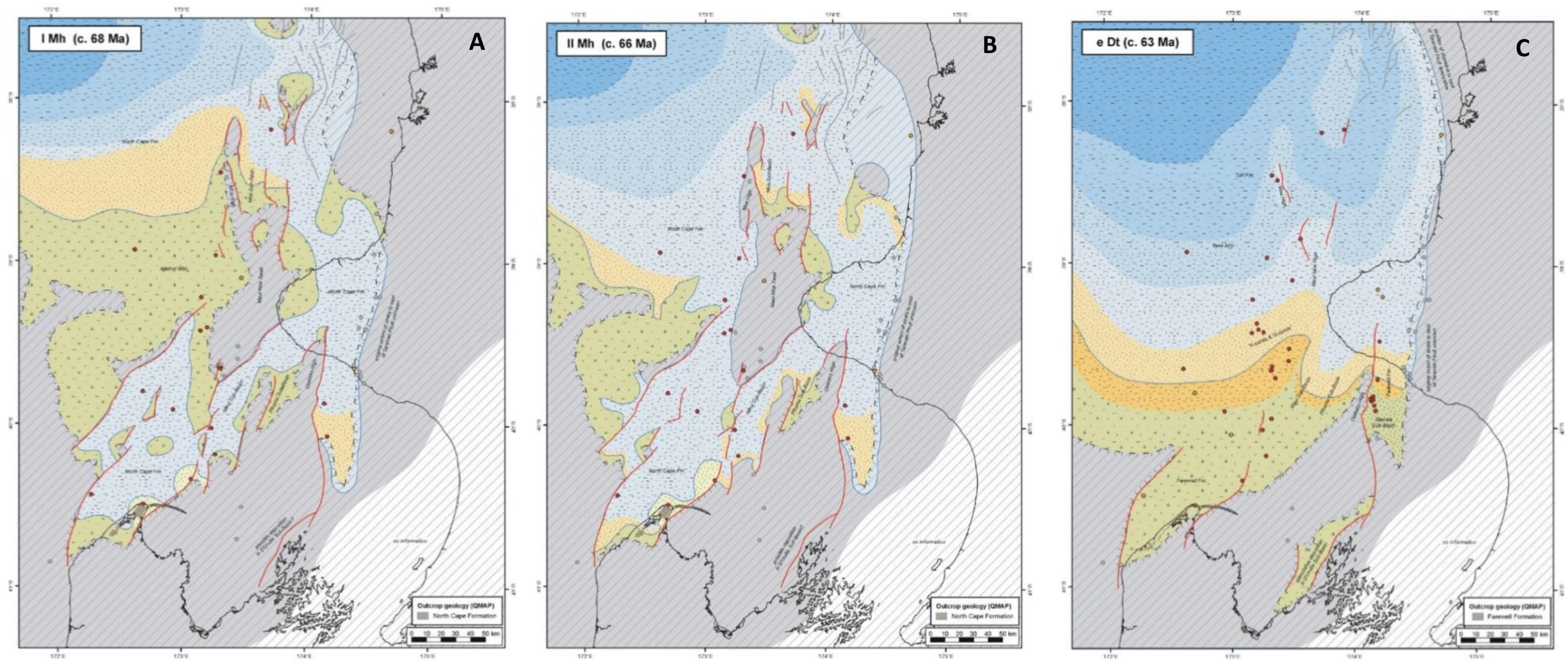
Toward the north of the Taranaki Basin the North Cape Formation is interpreted to have had the greatest marine influence due to abundant marine palynomorphs in the Ariki-1 well (Crosbie and Clowes, 1984). These units are dominated by non-reservoir mudstone and siltstones. In other regions the North Cape Formation deposited in the latest Cretaceous comprises more substantial sandstone beds with local interbedded coals and mudstones that have variable marine influence. Higgs et al. (2010) discuss the palynology and foraminiferal analyses at many well sites (Wainui-1, Taranga-1, Kiwa-1, Pukeko-1 and Cook-1) that have led the interpretation of a shallow to marginal marine paleoenvironment for a number of North Cape units.

Higgs et al. (2010) describe the two instances of core of the North Cape Formation, retrieved from the Tane-1 well on the western platform of the Taranaki Basin. These comprise upper, clean, well sorted, fine- to medium-grained, glauconitic sandstone with slight laminations that are interpreted to represent shallow marine deposition, while a lower core records slightly argillaceous, cross-laminated to ripple-laminated and fine-grained sandstones interbedded with carbonaceous mudstones and coals. These deposits are considered products of channel and floodplain deposition, with local peat mire deposits.

North Cape Formation outcrop samples, from the onshore portion of the Pakawau sub-basin have yielded dinoflagellates, marine algae and distinct sedimentological evidence for coastal and tidally influenced deposition, with ripple cross laminations, double mud drapes and bi-directional crossbeds consistent with a tidally-influenced marginal marine, likely estuarine depositional environment (Bal, 1992; Wizevich et al., 1992; Bal and Lewis, 1994). The recognition of the structures was achieved through thorough investigation of sedimentary lithofacies within available Late Cretaceous North Cape Formation outcrop. This was done in order to categorise characteristic lithofacies into associations that could be used to assign depositional environments and subsequently evaluate petroleum propsectivity of the Late Cretaceous successions.

The three recognised lithofacies associations that have provided a stratigraphic framework for categorisation of the lithofacies associations presented in this research were established by Higgs et al. (2010) based largely on the previous works of Bal and Lewis (1994);

> A1 – thick-bedded, fine- to coarse-grained sandstone, often cross-bedded with mud drapes;
>
> A2 – thinly bedded and laminated (pin-striped), very fine- to fine-grained sandstone with mudstone, claystone, and coal;
>
> A3 – thinly bedded fine-grained sandstone with alternating mudstone, rare conglomerate and coal seams.



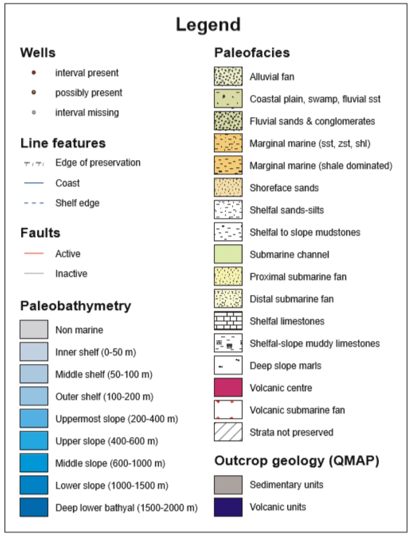


Figure 1.4 – Paleogeographic reconstruction of the Taranaki Basin during the deposition of the Late Cretaceous sequences of the Pakawau Group. Maps after Strogen et al. (2011).

A: Paleogeographic map for 68Ma (Late Haumurian), where the early development of the North Cape Formation occurred. Much of the Taranaki Basin was flooded forming a shallow marine shelf, with a number of intra-basinal highs that likely had no Late Cretaceous deposition. The majority of North Cape Formation is assigned to shoreface sandstones, with the potential of some coastal plain deposition in the lowermost successions.

B: Paleogeographic map for 66Ma (latest Haumurian), encompassing the latter stage of North Cape Formation deposition in the Late Cretaceous. Marine transgression continued, covering much of the Taranaki Basin in shallow marine shelfal environments. In the Pakawau Sub-basin the North Cape Formation is shown as shoreface sandstones to shelfal sandstones

C: Paleogeographic map for 63Ma (early Teurian), where early development of the fluvial-shallow marine Farewell Formation took place. Faults in the Manaia and Pakawau sub-basins continued to exert control on the position of the shoreline. By this time deposition is assigned as entirely coastal plain, with swamp deposits and fluvial sandstones of the Farewell Formation.

1.5 – Thesis objectives and structure:

This thesis predominantly covers lithofacies analysis of NW Nelson's North Cape Formation in order to understand depositional setting and paleogeography in the Pakawau sub-basin throughout the Late Cretaceous and combines assessment of new and existing sedimentological analysis of the North Cape Formation in order to:

- Define, in high-detail, the variations in lithofacies across available North Cape Formation outcrop within present day Whanganui Inlet;
- Assign clear lithofacies associations in order to define paleodepositional settings and make inferences to the paleogeography of the southern Taranaki Basin;
- Compare the interpreted depositional setting of the North Cape Formation to modern and ancient analogues;
- Determine the reservoir potential of the onshore equivalent North Cape Formation, through assessment of individual facies petrophysical properties;
- Combine sedimentological, petrophysical and analogue analyses to establish the application of findings to the offshore equivalent North Cape Formation units;
- Establish a better understanding of mixed-energy estuarine environments in actively subsiding rifts,

There is a significant focus on sedimentary lithofacies descriptions, the subsequent interpretation of depositional setting (Chapter 2). Sedimentological descriptions are organised based on their position in the lithofacies table (table 2).

These interpretations are then used in the reconstruction of the paleogeography based on the present day Whanganui Inlet's outcrops both laterally and vertically through stratigraphy in Chapter 3. Lithofacies are grouped and classified into broad lithofacies associations, defined by depositional setting and compared with modern and ancient analogues (Chapter 3). Later in the thesis there is an assessment of reservoir potential of the units within the North Cape Formation which incorporates previous interpretations and petrophysical properties of the units with well data (Chapter 4). The final chapter summarises the interpretations presented throughout this thesis and indicates the relevance of these findings in both a local and global context (Chapter 5).

Chapter 2 – Sedimentology

2.1 – Introduction

Despite the long history of exploration and sedimentological assessment of the Taranaki Basin's Cretaceous deposits it wasn't until Wizevich et al. (1992) that the North Cape Formation was formally recognised as a fluviomarine succession of probable estuarine origin. The characterisation of these depositional settings is important in the consideration of the analogue potential of Late Cretaceous rocks as depositional settings have both hydrocarbon source and reservoir rock potential within the greater Taranaki Basin.

Sedimentological analyses of the North Cape Formation outcropping along the eastern shoreline of the Whanganui Inlet in NW Nelson undertaken in this thesis and previous work has yielded sedimentological evidence indicative of marine influence within the North Cape Formation, with a number of dinoflagellate and marine algae species (Wizevich et al., 1992). The former braided river model for the deposition of these units was revised to a tidally influenced, marginal marine environment, with authors characterising lithofacies to determine depositional systems across the study area (Bal, 1992; Wizevich et al., 1992; Bal and Lewis, 1994; Wizevich, 1994; Stark, 1996; Higgs et al., 2010). Detailed sedimentary facies analyses assigned progradational successions of estuarine, fluvial, floodplain and mire deposits, where the overall depositional setting represents a macrotidal estuary with prograding fluvial dominated deposition (Wizevich et al., 1992; Bal and Lewis, 1994; Higgs et al., 2010). These analyses facilitated broad scale attempts to categorise lithofacies associations across the North Cape Formation within the Whanganui Inlet, to enable reconstruction of paleodepositional processes and establish controls on reservoir quality for these Late Cretaceous rocks (Higgs et al., 2010).

Although the depositional interpretation of the North Cape Formation is now accepted as fluviomarine to estuarine, definition of the lateral variations in lithofacies to establish more localised depositional processes has been less of a focus. The research presented here focuses on the variation in sedimentological character of the North Cape Formation across its expression in the Whanganui Inlet area.

The classic oceanographic definition of an estuary is a semi-enclosed body of marine water that is measurably diluted by freshwater (Pritchard, 1967; Nichols and Biggs, 1985). This definition focuses on changes in salinity and the subsequent effects on fauna in an estuary, which for the purpose of this study is too broad and difficult to establish from the rock record. Instead, the present work adopts the works of Dalrymple et al. (1992) where an estuary is defined as a flooded valley on a transgressive shoreline that receives sediment from both marine and non-marine sources. The lithofacies that comprise an estuarine sequence are controlled by the relative role of rivers, tides and waves (Dalrymple et al., 1992). Frey and Howard (1986) describe an estuarine sequence as a complex of intertidal, shallow subtidal, mostly channel form facies that are at least to some extent dominated by tidal processes. It is expected that the relative role of rivers, tides and waves vary within different parts of an estuary, thus affect the variety and distribution of lithofacies in an estuarine sequence. Estuarine facies ultimately exhibit obvious variations in texture, composition, and in physical and biogenic sedimentary structures. The depositional environments that comprise an estuary can include any or all of the following: tidal deltas, inlets, shoals, back-barrier beaches and spits, swash and point bars, tidal flats, marshes, stream banks and channels. As such, it is important to consider variation in lithofacies in detail in order to accurately define depositional processes and understand the geometry of the distinct depositional sub-environments in an estuarine setting. Tide-dominated estuaries have considerably more limited data sets than their wave-dominated counterparts so this study aims to expand depositional models, with more detailed analysis of a mixed energy estuarine environment (Tessier, 2010).

2.2 – Research methods

Field work was conducted in the remote area of Whanganui Inlet, NW Nelson. Field investigations included examination of previously published sections and measurement of new stratigraphic sections and in-situ measurement of petrophysical properties of the strata.

Nine new measured sections are included this study in addition to edits and additional commentary on three published sections across the Whanganui Inlet (Higgs et al., 2010). Hand-held global positioning system (GPS) coordinates (WGS 1984) were taken periodically through section measurement in order to locate the top and base of the sections and locations between. Figure 1.3 denotes the location of each measured section, with the coordinates collected at the base of each section used to represent location.

Measured sections were first described on a bed-by-bed basis, progressing from the base of the available section to the overlying bed(s). Stratigraphic units were measured to centimetre-scale; with small scale features useful for interpretation down to millimetre-scale included where necessary. Descriptions included standard bed thickness, colour, sedimentary textures, structures, nature of contact and lateral extent of the measured beds. Composition is not a focus of this research so was not considered beyond basic field description.

Measurement of paleoflow was conducted using a geological compass and a flat projection surface on suitable structures including cross-beds, ripples, coalified wood branches or fragments and surface lineations. The quality of measurement varied significantly within sections and across outcrop localities so therefore a rating of confidence was noted (A-C, with A being a reliable reading and C the least confident reading). Where possible a quantitative direction was assigned, although for some only an average direction or trend could be determined. The nature of the shallowly dipping North Cape Formation resulted in no need for rotation of these measurements.

Samples were collected where outcrop was suitable using a geological hammer. These samples were collected for different facies in order to conduct petrophysical analysis on their permeability and porosity characteristics (later chapters). Any samples collected were done so in accordance with DOC requirements determined by a sampling permit for the field area or based on the permissions of relevant land owners.

2.3 – Lithofacies

Thorough outcrop descriptions have been used to identify 10 distinct lithofacies and subsequently assign three lithofacies associations (discussed in Chapter 3) to outcrop of the North Cape Formation in the study area. The individual lithofacies are shown in Tables 2.1, 2.2 and 2.4. An interpretation of depositional environment is also included. The ten lithofacies that comprise the established lithofacies associations are first described individually then discussed collectively in their assigned Lithofacies Associations in Chapter 3 as part of a broader interpretation of the paleogeography of the region.

2.4.8 – Conglomerate (G)

Conglomerate (G) lithofacies are brown-dark grey when highly cemented, with commonly weathered outer surfaces that obscure structure and textural detail. Beds are typically well indurated though fresh surfaces are often more friable.

G facies varies from granular to medium pebble, with rare cobble sized clasts, though an average medium pebble clast size is typical. These units are moderately sorted with visible matrix and clasts sub-angular to sub-rounded. Clasts are somewhat oblate and do not show any obvious imbrication or preferred clast orientation. **G** facies is clast supported, with the proportion of matrix varying from 20% - 40%.

Conglomerate **(G)** beds are observed as either laterally continuous tabular bodies, like those seen at Pecks Point, or as significant channelised structures with erosive bases. Beds are crudely horizontally- and cross-stratified, indicated by centimetre thick intercalated medium- to coarse-grained sandstone layers. Fine grained discontinuous lenses or small drapes appear throughout **G** lithofacies. These drapes are generally muddy siltstones but can be as coarse as fine sandstone. Lenses exhibit concave upwards bases and can extend 2m laterally and be up to 20cm. Small current ripples and flame structures are occasionally present within the lenses. More massive conglomerate **(G)** beds, particularly through Pecks Point are seen to interfinger with sandstone lens-shaped bodies of lithofacies **Sxt** and **Sw**. These lenses vary in thickness and extent, with some extending as far as 15m of visible outcrop though not exceeding 30cm in thickness. These lenses contain occasional small cross bed sets and current ripple forms. Occasional coalified wood fragments are present within **G** facies in the Pecks Point North and Maori Point sections. There is no common orientation to these fragments, and they range in size from 7cm up to 35cm in length. Organic stringers have been observed in some beds, though these are relatively rare and do not typically exceed 6cm in length and 0.5cm in width. Some beds extend at least 30m across outcrop. Units are thickly bedded, averaging 1m thick, but ranging between 30cm to 4m.

Distribution of this lithofacies is strictly limited to the northeastern outcrops in the field area.

Interpreted depositional environment:

G lithofacies is interpreted to represent deposition within high energy channels, with frequent diagnostic concave upwards, erosive basal contacts observed in outcrop. Massive to horizontal and crude cross bedding interfingered with Sxt and Sw lithofacies indicate gravel bar deposition with intervening sandstone channel fill (Miall, 1978; Bal, 1992). The sub-rounded clasts that average medium pebble in size indicate deposition occurred a moderate distance from the sediment source, interpreted to be derived from the Whakamarama Fault to the east of the study area (figure_).

Although mud draping occurs there is no evidence for paired drapes consistent with tidal influence, thus it is expected tidal influence was minor to non-existent during deposition of these successions.

Previous investigations have assigned conglomeratic facies in the study area to represent localised fan delta systems (Bal and Lewis, 1994; Higgs et al., 2010). The lack of matrix supported conglomerates, angular clasts and the relative distance from the Whakamarama Fault limit the ability to assign alluvial fan influence to this facies. As such this research would like to also consider this lithofacies as representing deposition in a gravelly delta environment.

Table 2.1 – Conglomerate lithofacies of the North Cape Formation, Whanganui Inlet, NW Nelson.

Lithofacies (code)	**Texture**	**Description**	**Sedimentary Structures**	**Bioturbation**	**Distribution**	**Depositional Environment**
Conglomerate **(G)**	**Medium Pebble** (Granular - Pebble. >50% gravel)	Massive, planar, thickly bedded (dc-m scale) clast supported moderate to well-sorted bed sets. Sub-rounded granule to coarse pebbles with no obvious imbrication. Common erosive bases with concave upwards lower contacts.	Discontinuous silt/mud drapes . Rare organic stringers and occasional coalified wood fragments.		Limited to northern region	Gravelly delta (Flood events, high energy channels)

2.4.7 – Crossbedded Sandstone (Sx)

Crossbedded sandstones represent major constituents of North Cape Formation sediments. These units are widely distributed throughout the study area, where each outcrop contains crossbedded structures. The lithofacies ‘cross bedded sandstone’ considers compound cross bed sets and is comprised of two sub-facies; **Trough crossbedded sandstone (Sxt)** and; **Planar tabular crossbedded sandstone (Sxp).** Bed colour varies between tan-brown in fresh surface exposures to dark grey with more strongly weathered outer surfaces. Facies **Sxt** and **Sxp** are observed as individual beds or within larger bodies alongside massive or wavy bedded sandstone, with cross bed sets seen to typically grade into this facies.

Figure 2.1 –

Left: Typical internal structure of **G** lithofacies. Note: some evidence of trough crossbedding indicates by intercalated medium sandstone layers, Pecks Point CGL outcrop. Geological hammer for scale (30cm)

Bottom: Channelised base of a conglomerate bed, **G** facies, with distinct siltstone and sandstone rip ups incorporated from underlying **Hl** facies, Pecks Point Cgl outcrop. Metre rule for scale.

2.4.7.1 – Trough Crossbedded Sandstone (Sxt)

Facies **Sxt** varies in grain size from fine to very coarse sand with local granules and fine pebbles. Where granular and pebbly grain sizes are present beds most often contain sub-rounded grains, and are moderately to poorly sorted. Dominantly sandy Sxt facies are moderately sorted, displaying less obvious fining up sequences.

Trough crossbed sets of varying extent and size characterise **Sxt** facies. Individual crossbeds are typically well-sorted with clear fining upward sequences up to foresets which are commonly capped with mud or fine silts. These can range from 5cm up to 2m in height. These are occasionally seen to be bi-directional. Mud drapes and silt lenses are very common within lithofacies **Sxt**, varying in size and extent, with some up to 1m across and 15cm thick. In the northernmost sections double mud drapes are observed in stacked cliff faces.

Size and extent of **Sxt** units varies across measured outcrops with some units as thin as 10cm and typically no greater than 40cm, though in northern regions these units can range from 50cm to 4m. Trough crossbedded horizons are relatively laterally extensive, being tracked for up to 15m where exposure allows. **Sxt** lithofacies typically forms as nested units, stacked through more substantial sandstone bodies and commonly interfingered with **Sw** facies. Overall some beds show fining upwards and reduced thickness of crossbed sets upwards, though coarsening can also be observed. **Sxt** beds often show distinct erosive, concave upwards bases and can often include rip-up clasts in lower portions of beds with occasional preservation of topsets.

Coalified wood fragments are abundant within **Sxt** facies. Pecks Point provides an excellent example where these are prevalent in thicker trough cross bedded units and at this locality coalified wood fragments show an overall preferred southwestern orientation. These structures are less common in the other measured sections and as a result no orientation measurements were taken at other localities.

A single cobble-sized boulder is incorporated within a coarse Sxt bed at the Pecks Point North and Mangarakau Swamp sections. This may represent a single coarse pebble lag or a drop stone, however the cementation leisegang bedding distorts view of the underlying sediment.

Sxt facies may contain rare J- and I-shaped vertical *Psilonichus* burrows, in addition to *Ophiomorpha,* particularly at Pecks Point*.* These vertical burrow structures are typically between 1cm-2cm wide and do not exceed 12cm in length. However, a few vertical structures extending from coarse sands into overlying or Hl facies are up to 20cm long and 5cm thick. Overall facies **Sxt** shows low diversity and low abundance of trace fossils.

Sxt facies was recorded at every measured outcrop, in varying scale and extent, although is most prevalent in the northern and southernmost sections. Units are more thinly bedded (cm-m scale) in central sections. **Sxt** facies is most commonly associated with **Sw** facies, interfingering to form more substantial units, although particularly in northern sections can be associated with **Hl** facies.

2.4.7.2 – Planar Tabular Crossbedded Sandstone(Sxp)

Planar tabular crossbedded sandstone (Sxp) is texturally similar to **Sxt** with fine sand to granular grain sizes. Sandstones and granules are sub-rounded and typically exhibit an overall moderate sorting.

Sxp facies are significantly less commonly observed in the field when compared with trough sets and tends to form individual tabular bed sets that ban be tracked up to 10m. These typically have sharp planar contacts and are clearly erosive features. Beds can often be seen to pinch out and appear to mark the base of concave upward channel sands and in these instances are observed in conjunction with underlying pebble lag bases.

Planar crossbed sets are typically no greater than 30cm in height, though 1-2m are observed at Pecks Point and stacked sets up to 6m in height were measured at Maori Point. Individual crossbed sets almost always display normally graded foresets with granules and coarse materials marking the base, fining up to distinct resistant silt to very fine sand drapes. All measured occurrences of **Sxp** were unidirectional. **Sxp** facies shows occasional reactivation surfaces on foresets with some mud drapes. This subfacies, unlike **Sxt** has not been observed to contain double mud drapes.

Sxp facies is most often observed in the northern outcrops, though is also present as small laterally discontinuous sets within larger sand bodies in the southeast regions of the study area.

Interpreted depositional environment:

The presence of both planar tabular and trough cross bed structures are consistent with dune migration in the lower flow regime. Trough cross-bed sets represent the migration of sinuous bed form dunes, while planar-tabular sets reflect constructive straight-crested dunes, or lateral accretion of channel forms (Reineck and Singh, 1980).

The presence of compound sets of cross beds within occasional coarsening upward sequences with intertidal signatures, such as double mud drapes and occasional low-diversity body fossils supports interpretation of intertidal sand shoal or mouth bar environment. Coleman et al. (1964) describes distributary mouth bar deposits as containing concentrations of wood fragments, abundant multidirectional trough cross laminations that are products of both wave an current acting on sediment. **Sxt** facies shows only a few coarsening upwards sequences so would assign this as representing larger scale tidal bar forms.

Figure 2.2 – *Top:* Coalified wood fragments within medium sands **Sxt** facies, Pecks Point North outcrop. Finger for scale.
Right: J-shaped vertical burrows, silt rip-up clasts and medium pebble lense within **Sxt** facies, Pecks Point North outcrop. Geological hammer for scale (head is 15cm).
Left: Relict boulder at the base of an **Sxt** bed, with leisegang bedding obscuring bottom contact, Pecks Point North outcrop. Ruler for scale.

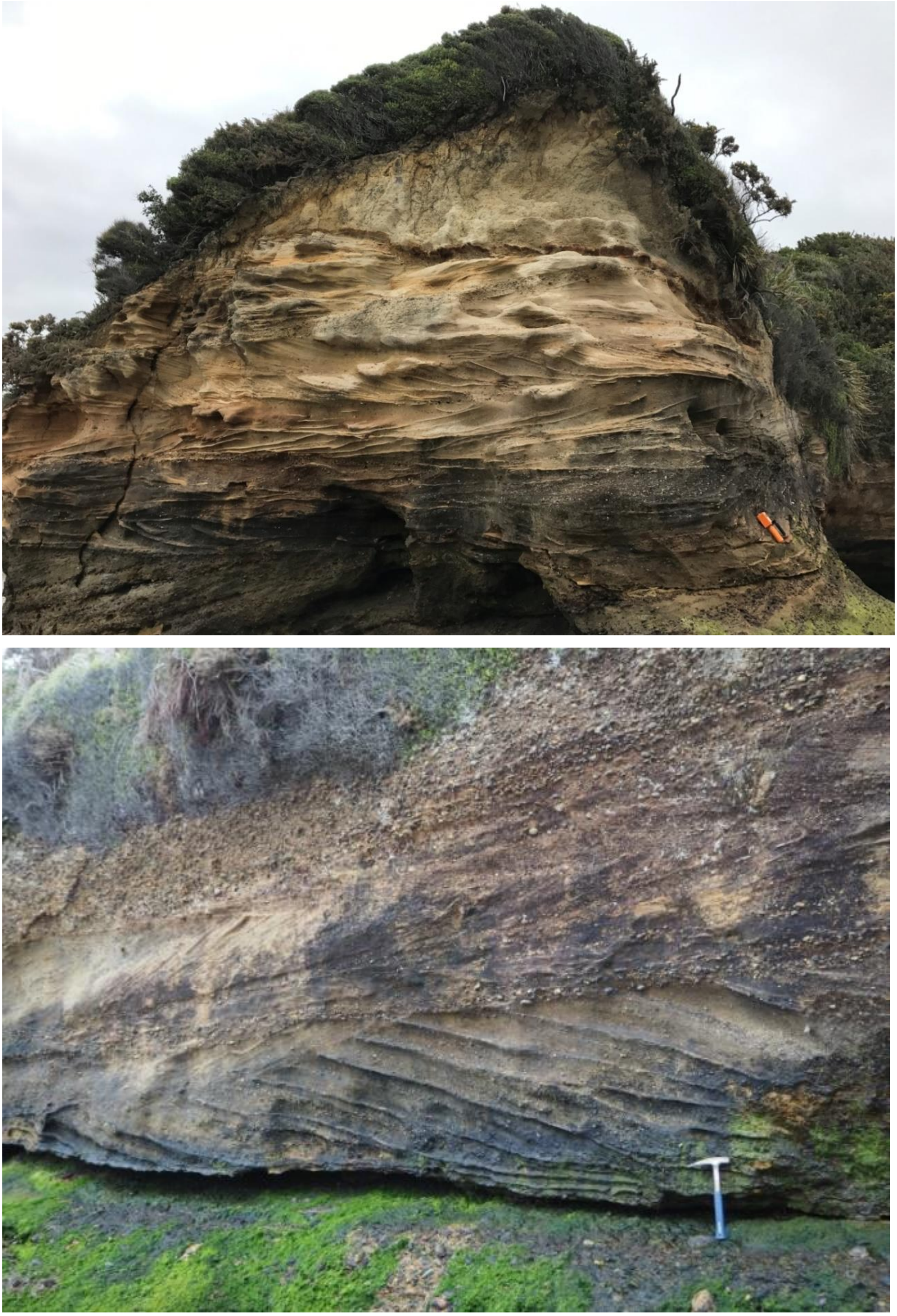


Figure 2.3 – *Top:* Channelised bases of thick **Sxt** and **Sw** facies with bi-directional crossbeds and mud drapes, Pecks Point North outcrops. Scintillometer for *in situ* gamma readings for scale (30cm).
Bottom: Low angle trough crossbeds of **Sxt** facies overlying a steeper trough crossbedded unit, Pecks Point North. Geological hammer for scale (30cm).

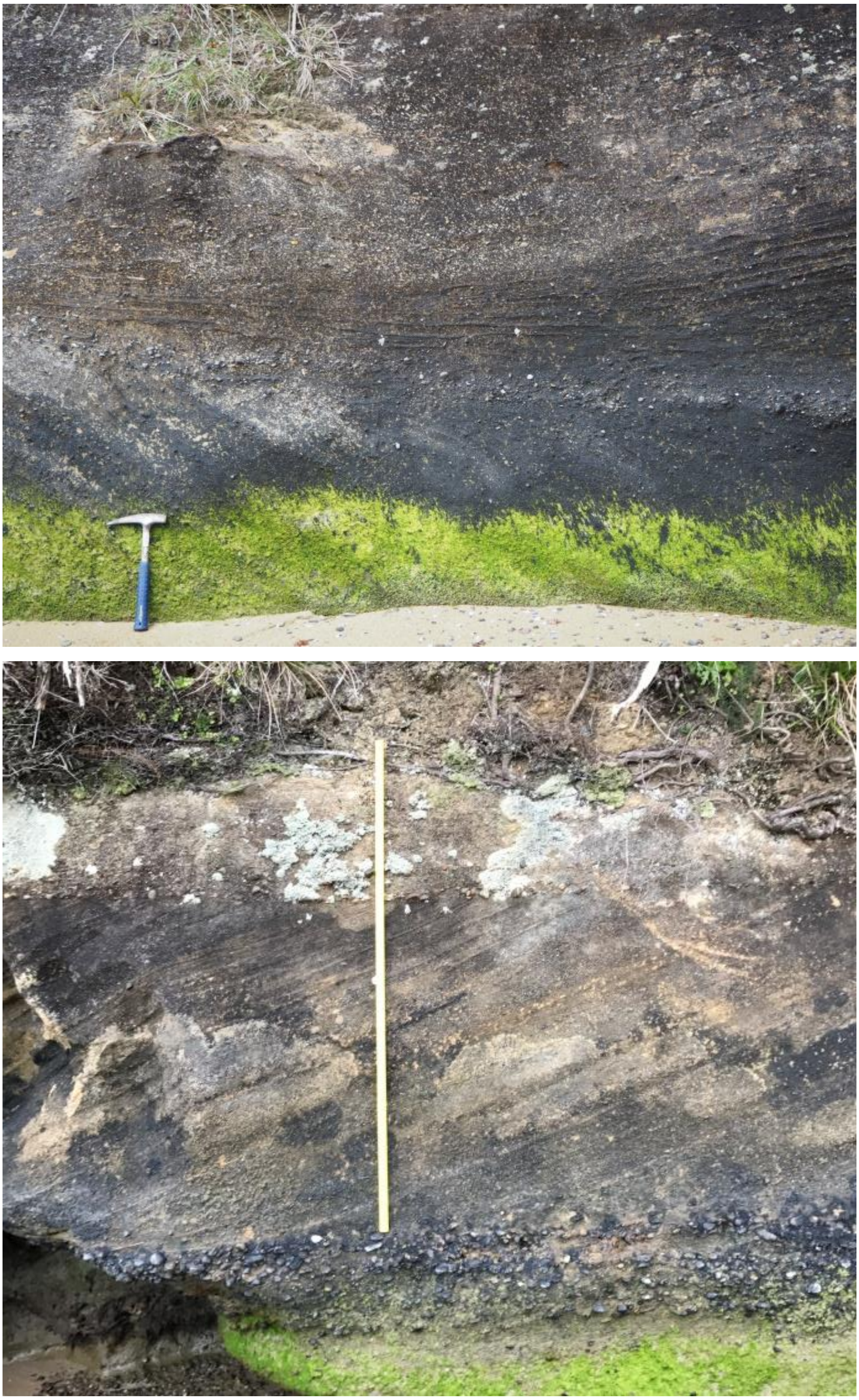


Figure 2.4 – *Top:* **Sxt** facies cut by granular to pebbly channel of G facies, Pecks Point North outcrop. *Bottom:* Planar tabular **Sxp** beds underlain by small **G** facies, note granular material marking foresets, Pecks Point North outcrop. Metre rule for scale.

2.4.6 – Massive to wavy bedded sandstone (Sw)

The **massive to wavy bedded sandstone (Sw)** facies is typically a brown grey colour, ranging from moderately indurated to easily friable and is usually weakly weathered. Facies **Sw** is described as massive to wavy bedded as a number of horizons show no obvious internal structure while others show distinct wavy bedding. Grain size appears to vary from very fine sandstone to very coarse sandstone with a mean grain size of fine upper sandstone. Central and western outcrops are dominated by fine sandstones, while northeastern outcrops are typically dominated by medium to coarse sandstones, with granules. Overall, facies **Sw** displays moderate to well sorted beds, with the exclusion of coarse channel lag and mudstone and siltstone rip-up clasts with sub-rounded grains where visible.

Sw facies are moderately bedded, commonly observed with erosive, concave upwards bases with horizons ranging from 1m – 3m thick, though facies **Sw** typically interfingers with crossbedded sandstones thus making it difficult to discern individual bed thicknesses. The overall structure of **Sw** units is characterised by small and incomplete local scours. Small channel structures are commonly observed within this facies, and can be accompanied by small ripples within and around the channels. Granular to coarse pebble lags often mark the base of **Sw** channel forms.

Mud drapes are highly prevalent in **Sw** facies, with some occurring as more significant discontinuous lensoid features up to 1m long and 20cm thick. There are some obvious double mud-drapes present with rip up clasts frequently also observed following drapes. Additionally, ripple forms and small scale flame structures are observed within some drapes, and within finer lenses of sandy material included as part of greater composite wavy and crossbedded sandstone horizons. **Sw** facies occasionally contains organic stringers. These are typically no more than 5cm in length and rarely more than 2mm thick so original source is difficult to discern. Additionally, northern measured sections contain occasional coalified wood fragments between 4 and 25cm in length, with no preferred orientation. **Sw** lithofacies also contains low diversity trace fossils with occasional *Ophiomorpha*, J- and I- shaped vertical *Psilonichus* present. The few trace fossil expressions did not exceed 7cm in length and 1.5cm in width.

Massive to wavy bedded sands are observed throughout the field area, however the extent and frequency is highly variable within outcrop. It is most commonly observed to interfinger **Sxt** and **Sxp** facies, forming large (metre scale) sandstone beds, although also occurs in thinner accumulations before and after expressions of facies **Hl** in the central outcrops.

Inferred depositional environment:

The dominant small channel and scour structures that include wave and current ripple forms indicate the presence of flowing water which are most likely small scale tidal channels flowing through or around bar structures. The presence of incomplete or crude cross beds leads to the interpretation of bar deposition; however some consideration of the more massive units where cross beds have not been able to form and the prevalence of double mud-drapes and burrows indicate that these features have some tidal influence.

Energy levels are high enough to result in the disruption of settled fines, producing rip-up clasts, though these are also products of channel processes and bank collapse, where bank material becomes incorporated into channel form. Mud rip ups at the base of beds are likely formed by higher energy currents ripping up muddy deposits of the previous slack-water period (Aschoff et al., 2016). The deposition of organic matter and mud drapes suggests periods of slack water or low energy flows, supporting the tidal classification, where double mud drapes are present.

Figure 2.5 – Interbedded Sw and Sxt facies, with coalified wood fragments and granules, Pecks Point North outcrop. 50cm ruler for scale.

2.4.5 – Planar laminated sandstone (Sp)

Facies **Planar laminated sandstone (Sp)** is defined by distinct planar laminations of siltstone up to medium sandstone and is commonly intersected by lens-shaped siltstone and sandstone bodies. Grain sizes vary between coarse siltstone to medium lower sandstone. Individual laminae are well sorted, parallel to bedding, with occasional small fining upwards cycles. Laminae vary between mm up to cm in thickness, with fine grain sizes distinguishable by colour.

Fresh surfaces show beds of dark brown to tan brown, depending on the dominant grain size of the individual laminae. Oxidation can give an orange-brown hue to some laminae. These units are weakly weathered, rarely cemented and moderately friable in most outcrop expressions. Induration of these units has shown to be affected by iron content, where diagenetic iron precipitate results in well indurated surfaces throughout the field area.

Figure 2.6 – *Top:* Rare relict cobble within alternations of heterolithic **(Hl)** and planar laminated sandstone **(Sp)** facies, Southern Inlet outcrop. Geological hammer for scale.

Bottom: Wavy bedded sandstone **(Sw)** with relict cobble interbedded with planar laminated sandstone **(Sp)** lithofacies, Southern Inlet outcrop. Ruler is 50cm for scale,

In central and southern sections beds are more moderately bedded, at a maximum of 6m at Wairoa River South section, though in this instance this bed alternated with massive sandstone and siltstone lenses. **Sp** facies is more thinly bedded in northern sections, with units not exceeding 1m and averaging 40cm. Structurally this facies forms laterally continuous tabular bodies, with basal contacts varying between sharp and gradational depending on stratigraphic facies relationships.

Various smaller-scale (millimetre-centimetre) sedimentary structures can be observed within these lenses; common cross-beds, flame structures and rare vertical burrows. Rarely associated with the cross-cutting sandstone lenses are small, single mud drapes. Organic stringers are commonly present within **Sp** facies, although do not usually exceed 6cm in length. Those recognised in **Sp** facies in the Mangarakau Swamp outcrop are more significant, reaching up to 25cm in length and up to 2cm wide (Figure 2.6). Additionally a single incidence of a relict cobble has been observed at the Southern Inlet outcrop.

This facies is widely distributed, though the extent of beds varies considerably across measured outcrop. There is a close relationship between **Sp** and the **Hl** facies, where they commonly occur as alternations in the central and southern sections presented in this research and the Oyster Point section published in Higgs et al. (2010).

Interpreted depositional environment:

The formation of planar laminated sandstones is consistent with upper flow regime plane bed deposition, typically abundant on beaches exposed to wave action in the swash zone (Reineck and Singh, 1980). Lithofacies **Sp** is well to moderately sorted and despite poorer sorting than typically expected in wave influenced deposition is interpreted to represent beach deposits that are less influenced by wave-reworking. Upper-flow-regime sandstones like those that characterise **Sp** lithofacies have been reported from axial portions of modern and ancient tide-dominated macrotidal estuaries (Dalrymple, 1992; Plink-Björklund, 2008).

This facies commonly occurs as thin expressions alternating with heterolithic interbedded sandstone **(Hl)** lithofacies reflecting the dynamic nature of the depositional environment, where depositional processes appeared to fluctuate relatively frequently. It is expected that slight increases in sea level and even slight wave action would be sufficient to redistribute sediment and created the well-sorted beach deposits of **Sp** lithofacies.

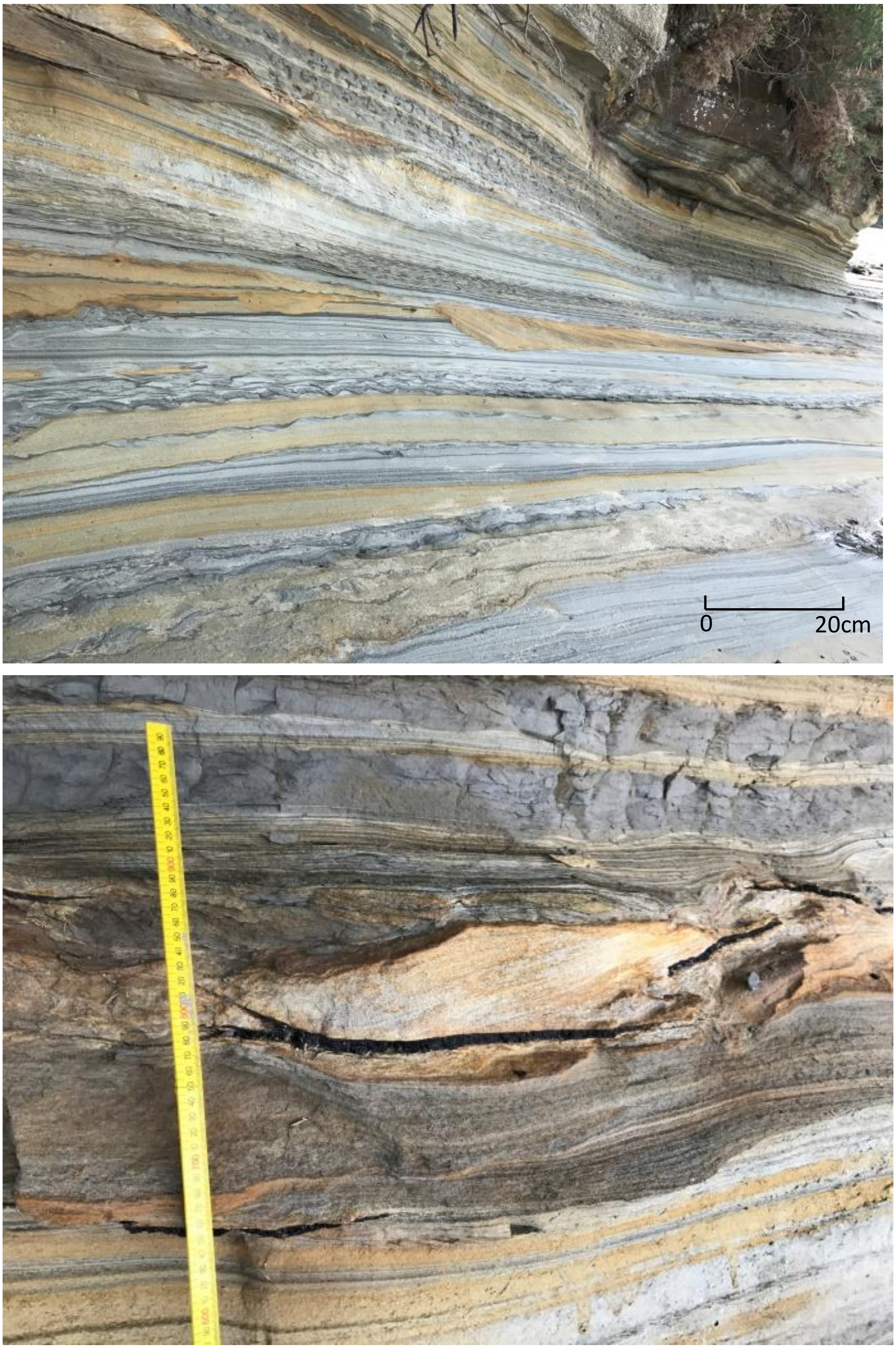


Figure 2.7 – *Top:* Alternations of planar laminated sandstone **(Sp)** beds with rippled heterolithic sandstone **(Hl)** beds at Mangarakau Swamp outcrop.
Bottom: Small crossbedded structures, indicating channel forms, with organic stringers, same bed as above photo (alternating **Sp** and **Hl** lithofacies), Mangarakau Swamp outcrop. Metre ruler for scale.

2.4.3 – Heterolithic sandstone (Hl)

The **heterolithic sandstone facies (Hl)** consists of interlaminated fine sandstone and siltstone. Overall grain size varies between fine siltstone to fine sandstones with small lenses of medium to coarse sandstone occasionally present.

Hl facies varies in colour although sandy interbeds are typically a light grey and stand out from the dark grey finer siltstone interbeds. In general these units are moderately indurated but sandstone beds that are grey appear strongly indurated than those that are yellow which are often more friable. Iron staining is common on bed surfaces and along small faults, as are iron nodules. The base of **Hl** units is always observed as sharp and planar.

Two sub facies are distinguished based on the dominant internal structure; 1) sub-horizontal parallel to wavy parallel interlaminated siltstone/fine sandstone and 2) ripple cross laminated fine sandstone interlaminated with siltstone. These structures commonly alternate within individual bed sets and rarely occur independent of one another.

These units provide excellent exposure of small scale tidal and deformational signatures, these will be described in detail separately then used to establish an interpreted depositional environment:

Flaser- bedding and starved ripple structures, with occasional lenticular beds, are very common in Hl facies in the Wairoa River sections. Additionally soft-sediment deformation structures are often observed within this facies, with flame and fluid escape structures particularly common, dominating a 25cm thick bed (Figure 2.8), and rare minor convolute beds no thicker than 20cm in central sections. The presence of very fine to coarse grained sandstone lenses, extending from 5cm to 30cm in length and containing current ripple structures, is common within **Hl** facies. Organic stringers are relatively uncommon in **Hl** facies, though stringers up to 30cm long and 2cm wide can be observed within silt dominated units.

Simple vertical burrows up to 7cm long and 2-3cm wide, in addition to dinoflagellates have been previously recognised in equivalent facies (Titheridge, 1977; Bal, 1992). **Hl** facies, particularly in the central sections of the field show a moderate diversity and abundance of trace fossils. These vary from abundant vertical *Ophiomorpha*, J- and I- shaped vertical *Psilonichus* burrows to rare *Macaronichus* burrows and thin angled burrows. Burrows range from 3cm-7cm in length and do not exceed 2cm in width. A single large branching burrow was observed in the Wairoa River North section, measuring 45cm in length and at its widest 8cm thick. Despite the moderate abundance of trace fossils **Hl** facies shows no obvious evidence of biogenic sediment mixing. Occurrences of **Hl** facies in northern outcrops do not record any obvious trace fossils.

Additionally this facies contains what are interpreted as probable dinosaur footprints. Described in Browne (2009), these structures were likely formed by Sauropod dinosaurs, herbivorous quadrupeds. Figure 2.10 shows the most convincing examples of these biogenic loading structures, in what were soft and soupy sediments where surrounding substrate was displaced around the foot {note location of these structures had been excluded for preservation purpose].

Overall unit thickness shows considerable variation across the field area. The north east yields significantly thinner accumulations of heterolithic sandstones that also appear less laterally extensive than those in the central, southern and north western measured sections. Central and southern sections show more significant accumulations of **Hl** facies, where individual beds can be up to 5m thick and are observed to be laterally continuous. However, in northern sections individual **Hl** beds do not exceed 1m and are frequently intersected by sandy channel forms, or appear to pinch out into other facies.

There is no definitive stratigraphic pattern for the occurrence of the heterolithic sandstone facies as they occur before and after all described facies, either as lenses or, most commonly, laterally extensive tabular bodies. **Sp** facies does commonly occur as interbeds with **Hl** facies, alternating from planar bedded **Sp** to wavy-parallel and rippled Hl facies throughout outcrop. The occurrence is slightly different with conglomerate facies where heterolithic sandstones appear in discontinuous lenses which are frequently ripped up and incorporated into other units.

Interpreted depositional environment:

The presence of starved sand ripples and flaser bedding provides important evidence for tidal influence. These structures form as a result of limited sediment supply, where sediment is often cut off within the depositional environment (Reineck and Singh, 1980). It can be interpreted that these are representative of slack and neap tidal bundles, where scours and ripples in the fine sands form during strong tides, while fine material in suspension infills the resultant 'lows' during slack tides. Additionally, the presence of *Skolithos* and *Psilonichus* Ichnofacies leads to the interpretation of brackish water conditions in estuary/bay to backshore sedimentary settings (Nesbitt and Campbell, 2006). Similarly, *Macaronichus* are interpreted as intrastratal grazing traces formed by deposit-feeding worms in intertidal to shallow-marine environments (Clifton and Thompson, 1978; Quiroz et al., 2010).

This depositional setting was also commonly cut by small scale channels, represented by lensoid sandstone structures scattered throughout outcrop. As such, **Hl** facies is interpreted as being deposited in a subaqueous tidal environment such as a lagoon or estuary floor to sand flat. The observed thin, discontinuous and often cross cutting beds of **Hl** observed in northern sections suggest a highly dynamic environment where channels switch and attempt to migrate, resulting in lower energy environments forming between. Additionally pre-existing topography may produce local highs in which tidal packages such as these can form without interference from channel processes. The occurrence of large Sauropod footprints described in Browne (2009) are consistent with a tidal setting in which water logged, swampy sediment is present. The interpretation of sub-tidal sand flat to estuary floor setting would be an expected habitat for large herbivorous dinosaurs to traverse. Preservation of biogenic loading structures, thin laminations and the lack of severe bioturbation in the Hl facies across the North Cape outcrop provide a good indication that the region maintained a relatively high sedimentation rate. Occurrences of up to 5m thick laterally continuous accumulations of Hl facies in central sections is most likely a product of the low relief and continued low energy related to an intertidal depositional environment.

Figure 2.10 – Records of probable dinosaur footprints:

Top: Footprint in plan-view within interbedded rippled heterolithic **(Hl)** and planar laminated **(Sp)** sandstone lithofacies, (location omitted for preservation). Ruler for scale.

Bottom: Footprint in cross-section, within interbedded **Hl** and **Sp** lithofacies, (location omitted for preservation). Ruler for scale.

Figure 2.9 – Trace fossils within the heterolithic interbedded sandstone **(Hl)** lithofacies:

Top: Left: Macaronichus trace fossils within very fine sand interbed of **Hl** lithofacies, Wairoa River South outcrop. Ruler for scale.

Right: Branching *Psilonichus* burrow within sandy **Hl** lithofacies, Wairoa River South outcrop.

Middle: Left: Organic stringers in silty **Hl** lithofacies, with lenticular sand beds and vertical burrows, Wairoa River North. Hammer for scale.

Right: Example of iron nodules and iron precipitate from diagenesis in **Hl** lithofacies, Wairoa River North outcrops. Hammer for scale.

Bottom: Large vertical burrow within **Hl** lithofacies into coarse trough cross-bedded sandstone **(Sxt)** lithofacies, Pecks Point North outcrop. Hammer for scale.

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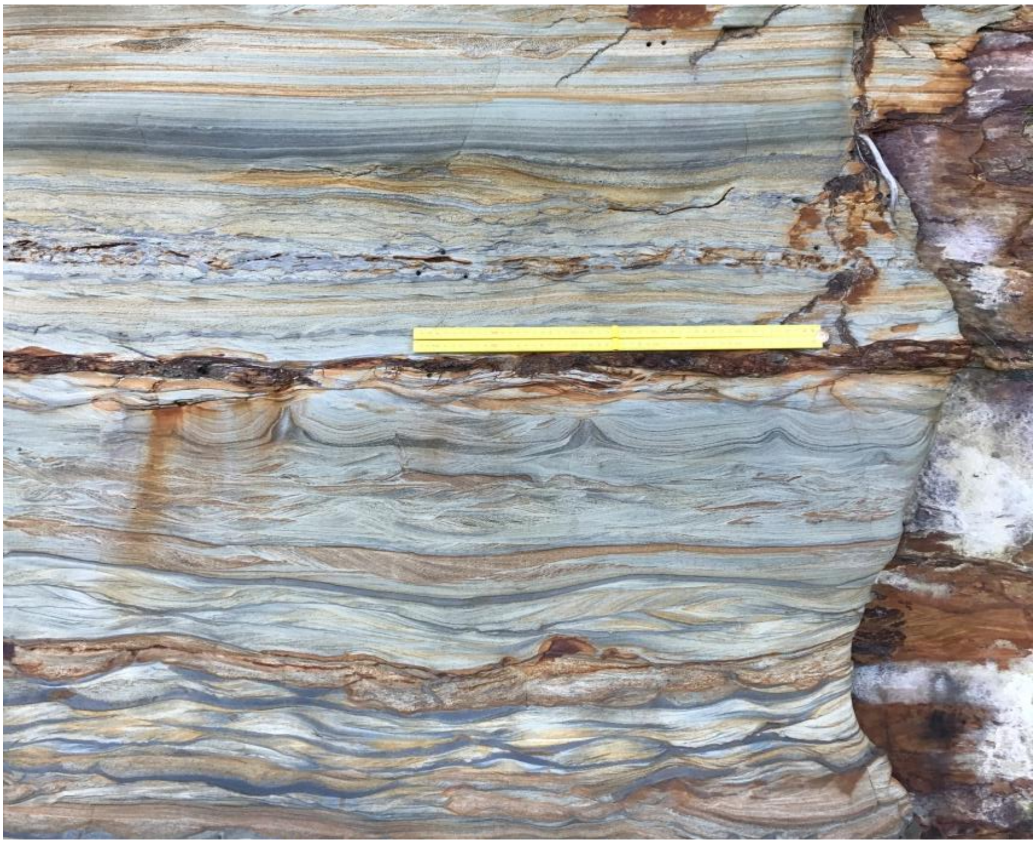


Figure 2.8 – *Top:* Fluid escape structures alternating with ripple cross laminated structures within heterolithic sandstone **(Hl)** lithofacies, Muddy Creek outcrop. 50cm ruler for scale.

Bottom: Flame structures in coarse siltstone and very fine sandstones of heterolithic sandstone **(Hl)** lithofacies. Outcrop shows common alternation of planar laminated sandstone **(Sp)** and **(Hl)** lithofacies Southern Inlet outcrop. Ruler for scale.

2.4.9 – Carbonaceous Sandstone (CS)

Carbonaceous sandstone (CS) facies is typically a bright blue grey to dark grey, although a number of expressions have an orange oxidised surface. Most units are friable though some are more indurated depending on the level of cementation.

CS facies is typically a well sorted, very fine sandstone ranging from coarse siltstone up to fine sandstone, with visible and abundant organic material present. Grains are sub-rounded where visible. Carbonaceous sandstones contain abundant organic stringers and occasional preserved leaf matter. No obvious trace fossils have been identified from these units, though when overlain by **C** facies **CS** units are lightly bioturbated by significant root structures. Rootlets can extend up to 30cm and are up to 4cm thick in some units.

Expressions of **CS** facies are typically thinly bedded, not exceeding 1m in thickness. Beds are tabular with planar, occasionally gradational bases and are relatively extensive with some being traced up to 20m laterally.

CS facies has limited distribution in the field area and is limited to northern and northwestern outcrops and is almost always followed by **C** facies as part of a fining upward cycle. It commonly follows **Sxt** or **Sw** facies and in one section is a lense within **G** facies.

Interpreted depositional environment:

The dominant fine sand and silt grain size in addition to abundant organic material settling suggest a lower energy flow that carries suspended fine grained material away from associated channel deposits. **CS** facies is inferred to represent fine crevasse splay deposits, in a proximal floodplain setting, due to the common proximity and occasional inclusion within channel forms. This facies shows no obvious tidal signatures and is closely related with clean, low sulphur coal varieties (**C** lithofacies), supporting an interpretation of fluvial influenced deposition. Rootlet bioturbation from overlying **C** lithofacies shows that all deposits are *in situ*.

Figure 2.11 - *Top:* Organic rich, fine sandstone **CS** facies, within **G** channel facies, Pecks Point Cgl outcrop. 25cm ruler for scale.
Bottom: Oxidised, obscured **CS** facies rich in organic material, Pecks Point North outcrop. 25cm ruler for scale.

Table 2.2 - Sandstone lithofacies of the North Cape Formation, Whanganui Inlet, NW Nelson.

Lithofacies (code)	Texture	Description	Sedimentary Structures	Bioturbation	Distribution	Depositional Environment
Trough crossbedded sandstone **(Sxt)**	**Medium sandstone** (F sandstone-medium pebble)	Trough crossbed sets vary from 15cm up to 2m. Commonly show gravel at base and contain frequent mud drapes. Commonly interbedded with wavy bedded sandstone. Occasionally beds fine upwards, though some coarsen upwards. Beds thicken up section at Pecks Point nth.	Low abundance, low diversity trace fossils. *Ophiomorpha* and vertical burrows	Present in all outcrops, thickness of beds is reduced in central region.	All measured outcrop, dominant in northern outcrops	Distributary channel, with migrating barforms and varying tidal influence
Planar-tabular crossbedded sandstone **(Sxp)**	**Medium sandstone** (F sandstone-medium pebble)	Crossbed sets range from 20cm up to 2m in height. Commonly gravel marks foresets, grading up to mud. Typically occur as individual sets though in small stacked sets can be observed at Pecks Point. No obvious grading overall.	Gravel foresets, occasional reactivation surfaces, mud drapes top of foresets.	Observed in most outcrops, though rare in central region.	Dominates northern region and rare in southern region	Distributary channel with migrating braid bars.
Massive to wavy bedded sandstone **(Sw)**	**Medium sandstone** (Vf - VC sandstone)	Planar to broadly lenticular very fine to very coarse, moderately to thick sandstone beds (dm-m). Moderately to well-sorted individual beds with common mud drapes and 'smiles' and erosive, commonly concave upwards bases. Common coarse channel lags and/or basal mud/silt rip up clasts.	Organic stringers, rip ups, silt/mud smiles all common. Occasional flame structures and rare relict boulders.	Low abundance, low diversity trace fossils. Ophiomorpha, vertical and J- and I-shaped burrows	All measured outcrop	Tidal sand ridges/or as part of channel dune structures
Planar laminated sandstone **(Sp)**	**Fine sandstone** (Coarse silt-M sandstone)	Planar beds of horizontally laminated (at mm-cm scale) dominantly fine sand to coarse silt, occasionally medium sands. No obvious grading overall. Well sorted. Sub-rounded grains.	Planar laminations. Occasional organic stringers and no mud drapes.	Low abundance of probable similar genera dinosaur footprints	All measured outcrops, though less significant in central region	Local beach
Heterolithic sandstone **(Hl)**	**Very-fine sandstone** (Coarse siltstone – fine sandstone)	Planar sets of parallel to wavy discontinuous interbeds of silt-fine sands (mm-cm scale). Non-erosive basal contacts. Common medium-coarse- grained sandstone lenses (5-25cm). Thin to moderately bedded (dm-m). Tidal signatures common throughout.	Current ripples and bi-directional ripple, starved ripple sets and flaser-bedding common, some flame structures, fluid escape structures and minor convolute beds. Occasional organic stringers and rare lenticular bedding. Muds yeild dinoflagellates.	Occasional local bioturbation and soft sediment deformation, with moderate diversity, moderately abundant burrows. *Ophiomorha,* J-, I-shaped vertical, angular and branching *Psilonichus* burrows. Low abundance of probable similar genera dinosaur footprints.	All measured outcrop, thinner beds in the north.	Sub-tidal zone
Carbonaceous sandstone **(CS)**	**Very fine sandstone** (Coarse silt - fine sandstone)	Planar to lenticular blue-grey beds, with limited lateral extent and sharp basal contacts. Moderately- to well-sorted beds, dominated by very fine to fine sands with organic stringers and coarse silts.	Abundant organic stringers and discontinuous silt laminae.	Common large scale rootlet structures extending up to 20cm into beds	Northern and northwestern outcrops.	Overbank crevasse splay

2.4.4 – Deformed heterolithic siltstone (DHl)

Deformed heterolithic siltstone (DHl) facies is a variant of **Hl** facies described previously, although it is considerably finer grained, dominated by siltstone with secondary very fine sandstone. There is a clear colour distinction between siltstone (dark grey) and sandstone (mottled light grey) layers and individual laminae appear very well sorted. The sandstone beds occur in small, deformed lenses, producing distinct lenticular bedding, varying from continuous to broken.

Beds are highly deformed either via local slumps, convolute beds or flame structures. Convolute bedding and fluid escape structures are common throughout this facies. Convolute beds are of moderate thickness, averaging 30cm and not exceeding 40cm. One slump structure (at the Southern Inlet outcrop) showed distinct angular blocks of coherent material within it, with the majority of them rotated to vertical [photo}.

DHl facies contains rare surface traces of relatively small scale burrows, with deformation destroying preservation. Facies **DHl** also records two incidences of what are probable Sauropod footprints, previously discussed in Hl facies.

DHl facies is observed within the southern and western outcrop localities, and was not present in the northern region of the field area. This facies is interbedded with **Hl** facies but may be overlain by **Zb** or **CZ** facies or in the Southern Inlet section by channelised medium sandstone of **Sw** facies.

DHl facies is typically thinly bedded with individual units not exceeding 40cm and averaging 25cm across the observable outcrop localities. It forms relatively sharp to semi-gradational basal contacts and has low lateral continuity. Within the Mangarakau Swamp section this unit seemed relatively laterally continuous though notably within the unpublished Southern Inlet locality these beds were distinctly lensoid in shape, reaching maximum lengths of 6m, before being cut off or intersected by overlying channelised sandstone bodies. As with other facies the dip of units and exposure along headlands limits the ability to track facies over considerable lateral distance.

Interpreted depositional environment:

The observed lens shapes, appearing to be cut off by channelised sandstones and the rotated nature of some instances of **DHl** suggest channel adjacent slumping with units moving into the topographic low formed by the channel margins. In order to facilitate a void significant enough to rotate entire blocks of coherent material it is inferred that this facies would have straddled a deeper channel prior to deformation. Additionally, lenticular beds indicate rhythmic bedding associated with a tidal setting (Reineck and Wunderlich, 1968) and the overall textural characteristics of facies **DHl** are similar to those of **Hl** facies so it is interpreted that they share the same depositional process and are simply separated based upon post depositional deformation.

DHl facies, characterised by prevalent post-depositional load structures, provides good evidence for rapid deposition from adjacent feeder channels with convolute bedding structures potentially related to sudden shear from rises in turbulence or the emergence of depositional layers and the liquefaction of underlying layer (Coleman, 1969; Reineck and Singh, 1980). The convolute beds observed at Oyster Point and Mangarakau Swamp represent the top of the sandy sequence which is commonly topped by **Zb** facies and followed by **CZ** layer. These sequences are common in interdistributary bay deposits and it is interpreted that the convolute structures in the North Cape Formation are likely associated with local regressive sequences and liquefaction from fluidisation of underlying layers (Coleman, 1969).

Figure 2.12 – Deformed heterolithic sandstone (**DHl)** lithofacies in plan-view on an exposed shore platform, showing lenticular beds, trace fossils and bioturbation from overlying **CZ** facies, Wairoa River South outcrop. Ruler for scale.

Figure 2.13 - *Top:* Lenticular bedding and probable dinosaur footprint in plan-view within **DHl** facies, on shore platform (location omitted for preservation). Ruler for scale.

Bottom: Convolute bedding in **DHl** facies on a shore platform, Mangarakau Swamp Shore outcrop. Ruler for scale.

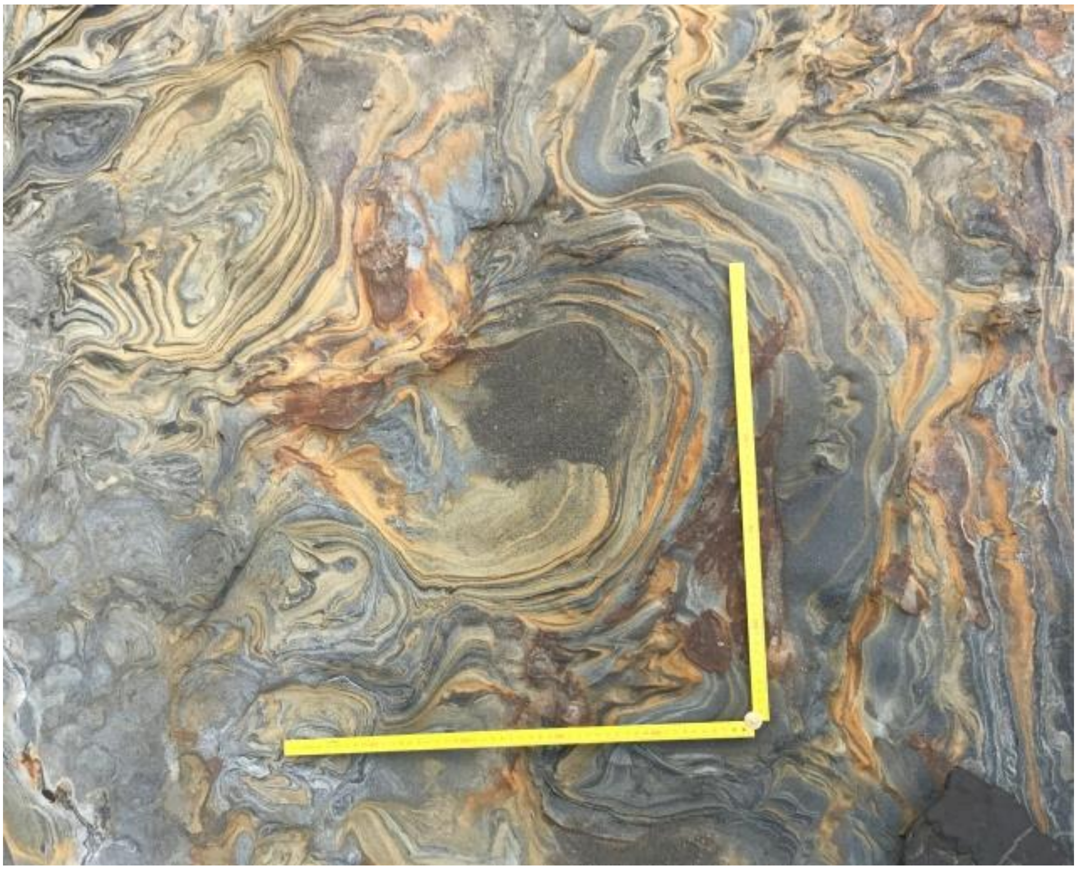


Figure 2.14 – *Top:* **DHl** facies with rotation of lenticular beds to vertical, showing clear relationship of **DHl** facies with channel processes, Southern Inlet outcrop. Ruler for scale.

Left: Lenticular bedding within rotated **DHl** facies, from top photo, Southern Inlet outcrop. Ruler for scale.

2.4.2 – Carbonaceous, bioturbated siltstone (Zb)

The **carbonaceous bioturbated siltstone (Zb)** facies exhibits a distinct brown-grey colour and is often strongly weathered resulting in typically flaky and friable outer surfaces. **Zb** facies are typically moderately- to well-sorted, with siltstone dominating most units.

Overall, facies **Zb** is thinly to moderately bedded, not exceeding 70cm and typically less than 30cm, although wavy to sub-horizontal planar laminations and interbeds are present. Facies **Zb** tends to form tabular units with gradational contacts, depending on the units below. When overtopping coal seams the contact is slightly clearer due to the colour difference, although when above heterolithic sandstone units often the contact is less obvious and more gradational.

Zb facies commonly contains well preserved leaf matter, with abundant carbonaceous stringers. When overlain by **CZ** facies, thin rootlet structures, no thicker than 2cm, are seen to extend down ~15cm into underlying beds. **Zb** facies shows obvious organic bioturbation. These include root structures extending from overlying **CZ** facies as well as a moderately diverse trace fossil assemblages with a number of vertical burrows varying between J- and I-shaped *Psilonchus*, *Ophiomorpha* and rarer surface traces of *Macaronichus.*

The lateral extent of **Zb** facies varies between outcrops and within measured section and in some sections is difficult to track across section due to the erosion of headlands. It is seen to pinch out laterally into facies **CZ**. The studied outcrops show a common transition from either **Zb** into **CZ** facies or vice versa. Additionally this unit is commonly observed in sequence from **Hl** and typically followed by **CZ** facies.

Facies **Zb** is only observed in sections along the eastern coastline of the field area, limited to the southernmost and central outcrop localities.

Interpreted depositional environment:

Facies **CZ** likely represents the highest part of the tidal zone; the tidal salt marsh environment. The presence of very fine grain sizes and thin carbonaceous stringers indicates a low energy, sub-aerial environment in close proximity to both brackish water and a terrestrial environment due to the presence of rootlets and abundance of marine trace fossils (Dalrymple, 1992). Rootlets also indicate vegetation was *in situ* rather than settled organic material that floated into the depositional setting.

The easily identifiable trace fossil species are within the *Skolithos* and *Psilonichus* Ichnofacies, which both favour variable grain size, sand and soft, typically unconsolidated substrates (Seilacher, 1967; Buatois and Mángano, 2011). *Psilonichus* Ichnofacies exhibit a range of inferred paleoenvironments with brackish water conditions, from coastal barrier islands, delta plains, lagoons and bays to estuaries, while *Skolithos* Ichnofacies are associated with beach, sandy tidal flats, shallow water and foreshore to wavebase paleoenvironments (Buatois and Mángano, 2011).

The abundance of plant material and moderate diversity of abundant trace fossils, with overall minimal sediment mixing and preservation of internal structures suggests a consistent and rapid sedimentation rate. Additionally the relationship of **Zb** alternating with **CZ** and obvious rootlets suggests there were ongoing, though gradual shifts in local water depths where vegetation could establish in the **Zb** facies to form thin, centimetre scale coal seams. The absence of oxidation staining or dessication cracks also supports interpretation of a relatively high water content reiterating that marginal tidal setting where inundation was likely common and intermittent (Dalrymple, 1992).

Figure 2.15 – Bioturbated carbonaceous siltstone **(Zb)** lithofacies with vertical trace fossils interbedded with discontinuous coal seams of silty coal **(CZ)** lithofacies, Wairoa River North outcrop. Ruler for scale

2.4.1 – Silty Coal (CZ)

Silty coal (CZ) facies is one of two variations of coal lithofacies. This lithofacies varies from bright and silky, to dull with mixed coal and siltstone seams and is typically very weakly weathered when higher proportions of silt are present. Overall this unit is moderately to poorly sorted with frequent mixing between coal and coarse siltstone. However, individual beds of clean coal and mixed siltstone and coal have also been observed.

Seams of **CZ** facies are typically thinly bedded, ranging from 5cm up to 35cm. These seams display relatively uniform thickness though the dip of units limits the ability to track these over significant lateral distance.

CZ facies is devoid of sedimentary structures with no obvious plant material preserved in the mixed coal/siltstone beds. Small root structures are often observed extending from **CZ** facies into lithofacies below. Rootlets are very thin, not exceeding 2cm in width and 15cm in length.

CZ facies has been observed in 2 different localities and is represented in 3 of the stratigraphic sections included in this study. These occurrences are limited to the eastern coastline of the study area, in the central and southernmost outcrop localities. Silty coal units are occasionally seen to pinch out, into **Zb** facies, and most commonly precedes and follows this facies in sequence. In some localities, where **Zb** isn't present **CZ** facies will precede or follow **Hl** facies.

Interpreted depositional environment:

CZ facies is interpreted to represent a salt marsh or coastal mire environment. The lack of entirely clean coal seams and relatively thin nature of coal seams within facies **CZ** supports a brackish water interpretation, as sporadic inundation of brackish water results in mixing between silt and carbonaceous material while also limiting significant vegetation growth. The presence of rootlets indicates these coals are *in situ,* and are not the result of transported carbonaceous mats floated in.

Bal (1992) reports distinct geochemical signatures in coal facies within the North Cape formation, with units measured along Mangarakau Swamp Shore reporting high sulphur and volatile contents, indicative of marine influenced deposition. Coals within the Bal and Lewis (1994) defined A2 association, which correlate to lithofacies **CZ** presented in this study, return sulphur contents in excess of 0.85% (Table 2.3) which reflect tidal influence with inundation of brackish water.

Table 2.3 - Coal geochemistry and categorisation of lithofacies associations relative to this study. Modified from Bal (1992).

Code (this study)	**Lithofacies Association (this study)**	**Lithofacies Association (Bal, 1992)**	**Framboids (Sulphur)**	**SE (specific energy) & VM (volatile matter)**	**Liptinite**
CZ	Association 3	Association 2 (Mangarakau Swamp shore section)	abundant	high	abundant (structureless and abundant liptodetrinite)
C	Association 1	Association 3 (Oyster Point)	no framboids (low sulphur)	low	low (laminae of cutinite and minor liptodetrinite)

Figure 2.16 – Thin, discontinuous coal seams of silty coal **(CZ)** interbedded with bioturbated carbonaceous siltstone **(Zb)** lithofacies, Wairoa River North. Metre ruler for scale.

2.4.10 – Coal (C)

Coal (C) facies are laterally extensive, clean coal seams. These are relatively bright and silky and frequently show rootlets at their base, extending to layers below, which are commonly carbonaceous sandstones **(CS).**

Seams range from 15cm up to 50cm thick, though commonly do not exceed 30cm. Seams display uniform thickness, showing lateral continuity in the observed outcrops, however the dip of the units means these layers can only be traced laterally for a few metres before extending below the visible surface. **C** facies contains more significant rootlet structures that extend up to 30cm into underlying units. These rootlets are notably thicker and more prevalent than those extending from **CZ** facies.

Clean coal representing facies **C** is only observed in two localities presented in this study, along the western margin of the field area. Limited accessibility of one of the outcrops has meant this facies is only represented in one already published stratigraphic section (Higgs et al., 2010) (6*) (see chapter 3). **C** facies is always preceded and capped by a silty to very fine carbonaceous sandstone facies.On a single occasion this facies is covered by **Sw** facies, with significant organic material and rip up clasts marking the base of the unit.

Interpreted depositional environment:

Thick, clean coal seams with large root structures, such as those present at Oyster Point and observed in outcrop along the western margin of the field area show low sulphur and depressed volatile contents which can be used to indicate a more fresh water source than those coals present within lithofacies **CZ**. As such, it is interpreted that the coals of facies **C** have been deposited on a floodplain, with little to no tidal influence. Coal beds representative of facies **C** have been described in previous studies which have also considered coal chemistry in defining depositional settings (Bal, 1992) (Table 2.3).

The presence of rootlets indicates the coal is autochthonous and in the Wairoa River South section coal beds in excess of 30cm indicate a lengthy depositional process, thus a slow switch from entirely non-marine back to tidal. Ryer and Langer (1980) report a 10:1 ration of compaction for Cretaceous peat to bituminous coal, so in order to produce seams in this thickness it would be expected that at least 3m of peat would have had to have been deposited. This considerable accumulation of organic material likely occurred over a long period of time. However, Nadon (1998) shows that realistic peat to coal compaction can be as low as 1.2:1 to 2.2:1, determined by sandstone channel geometries. This is a direct product of the moisture levels *in situ* and since they are unknown for this field area it is impossible to interpret the original thickness of the peat swamp.

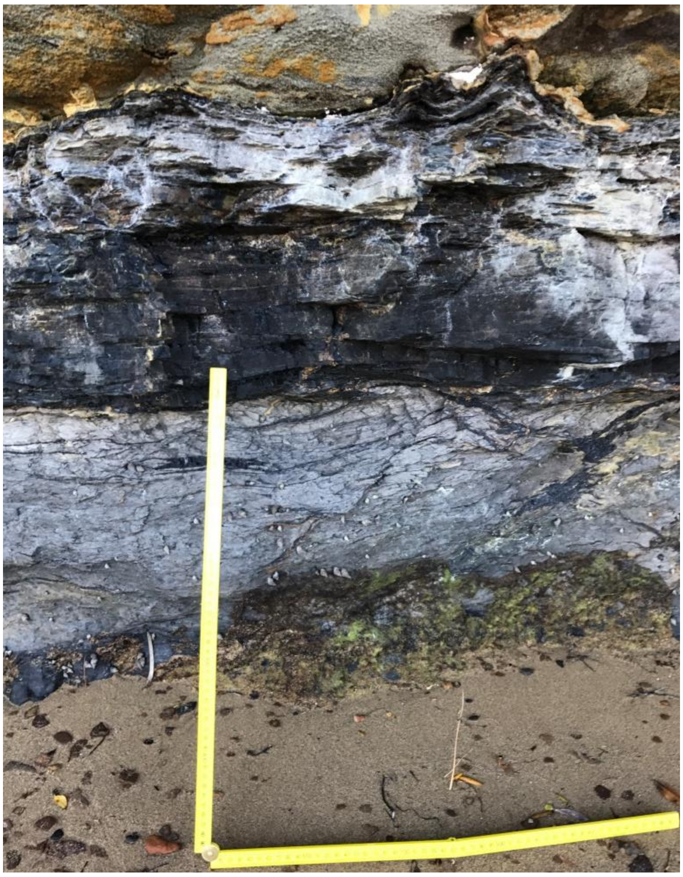


Figure 2.17 –

Left: Thick, continuous coal seam (**C** lithofacies) with substantial root structures extending into **CS** facies below, Southern Inlet outcrop. 50cm ruler for scale.

*Bottom***:** Thin expression of **C** facies interbedded with organic rich **CS** facies, Oyster Point outcrop. Camera lens cap for scale.

Table 2.4 - Siltstone and coal lithofacies of the North Cape Formation, Whanganui Inlet, NW Nelson.

Facies (code)	**Texture**	**Description**	**Sedimentary Structures**	**Bioturbation**	**Distribution**	**Depositional Environment**
Deformed heterolithic siltstone **(DHI)**	**Siltstone** (Mud-fine sandstone)	Deformed silt with very fine sands with wavy gradational base. May contain angular blocks of coherent locally derived heterolithic silt and sand units. Thinly bedded (dm) with common sharp, concave upwards bases.	Lenticular beds, flame structures very common and local convolute bedding (cm scale). Rare fluid-escape structures and no flaser beds.	Low abundance and diversity of vertical burrow structures. Single horizon includes probable dinosaur footprint.	Southern, central and western outcrops.	Tidal channel adjacent (slumps)
Carbonaceous bioturbated siltstone **(Zb)**	**Siltstone** (Mud-very fine sandstone)	Tabular beds of structureless to thinly laminated grey-brown, organic rich silt-very fine sandstone interbedded with carbonaceous stringers. Thinly bedded (cm-dm).	Common leaf matter, organic fragments and rootlets from layers above. Occassionally interbedded with silty coal and laminations of organic-rich muddy material.	Occasional, moderate diversity burrows, low-abundance Vertical burrows, *Ophiomorpha.* Surface traces, *Macaronichus.* J-, I- shaped vertical burrows. (assumed *Psilonichus*)	Western and central outcrops	Tidal salt marsh
Silty coal **(CZ)**	**Siltstone** (Mud-very fine sandstone)	Tabular to lensing, beds of dominantly silty coal with minor clean coal. Thinly bedded (cm-dm)	Rootlets extending to units below.		Central and southern outcrops.	Salt marsh
Coal **(C)**	**Coal**	Tabular, moderately bedded clean coal seams (dm scale). Bright, silky and dull varieties.	Rootlets extending to units below.		Western and central outcrops	Peat swamp

2.5 – Stratigraphic sections:

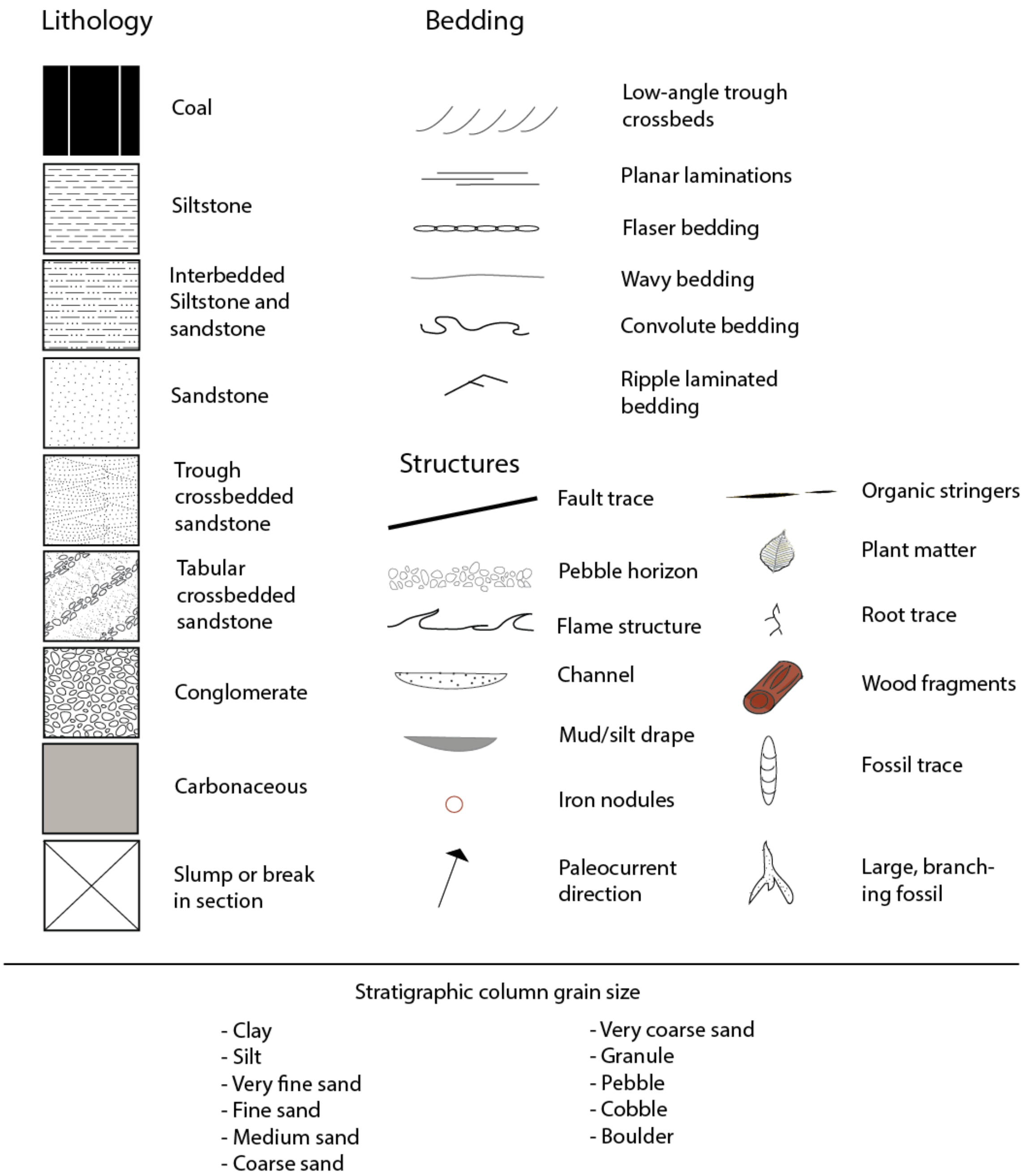


Figure 2.18 – Key for the stratigraphic columns presented in this thesis.

A

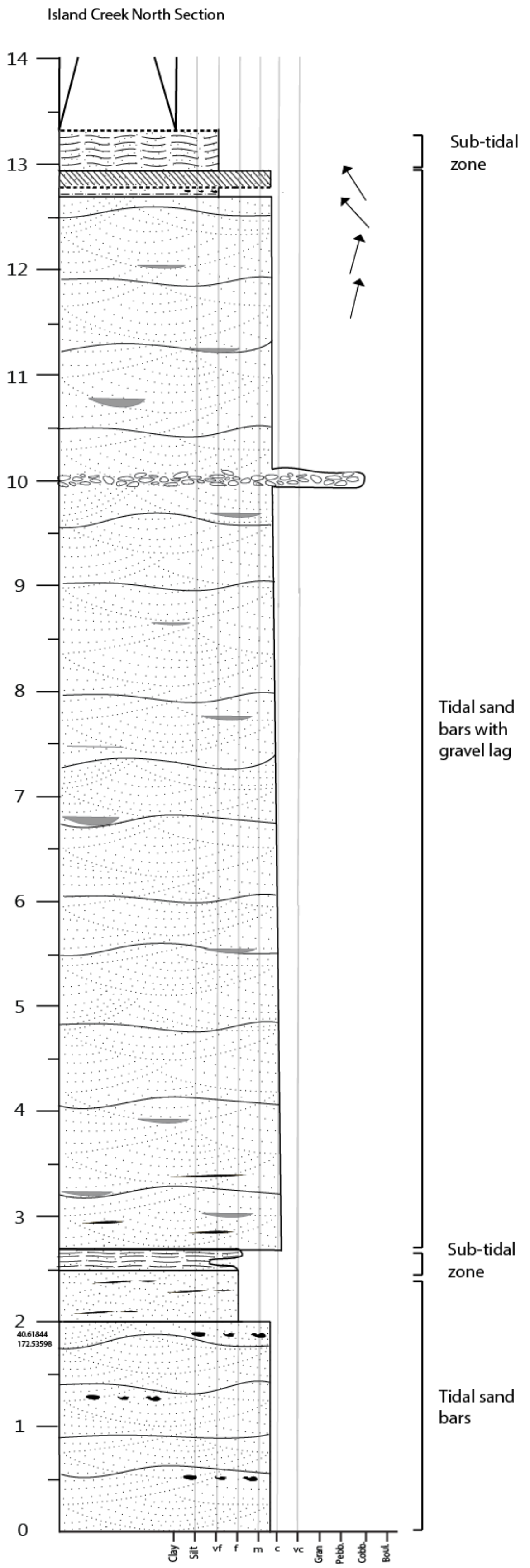
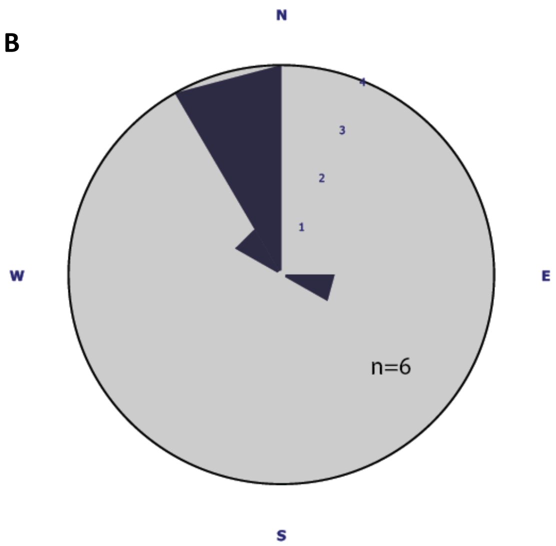


Figure 2.19 – A) Stratigraphic section for the base of the Island Creek Section (top of section follows in figure 2.20). **B)** Paleocurrent data for Island Creek stratigraphic section.

B



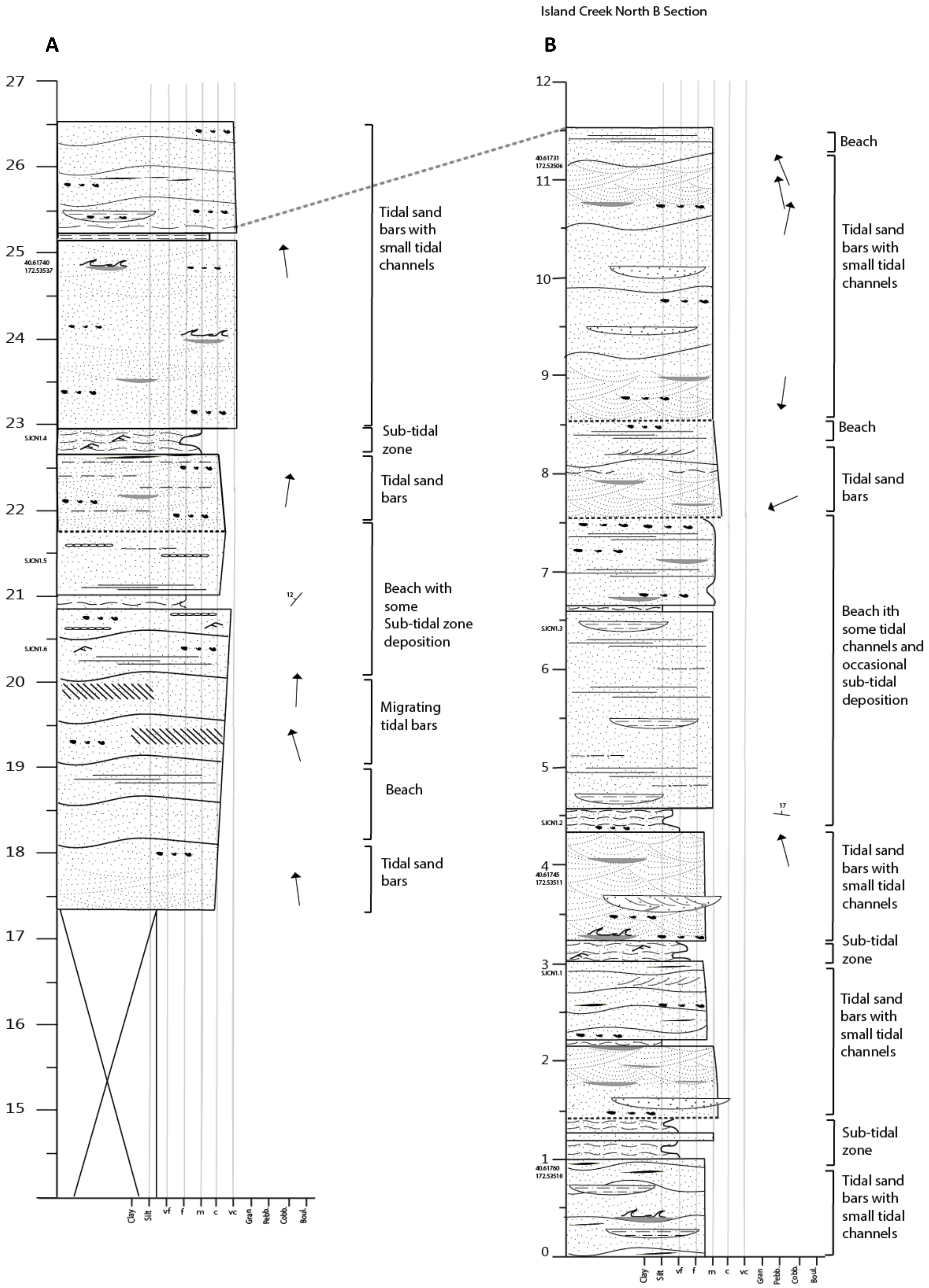


Figure 2.20 – A) Stratigraphic section for the top of the Island Creek locality presented alongside the laterally equivalent section **(B)** which outcropped around a headland going back down stratigraphic section.

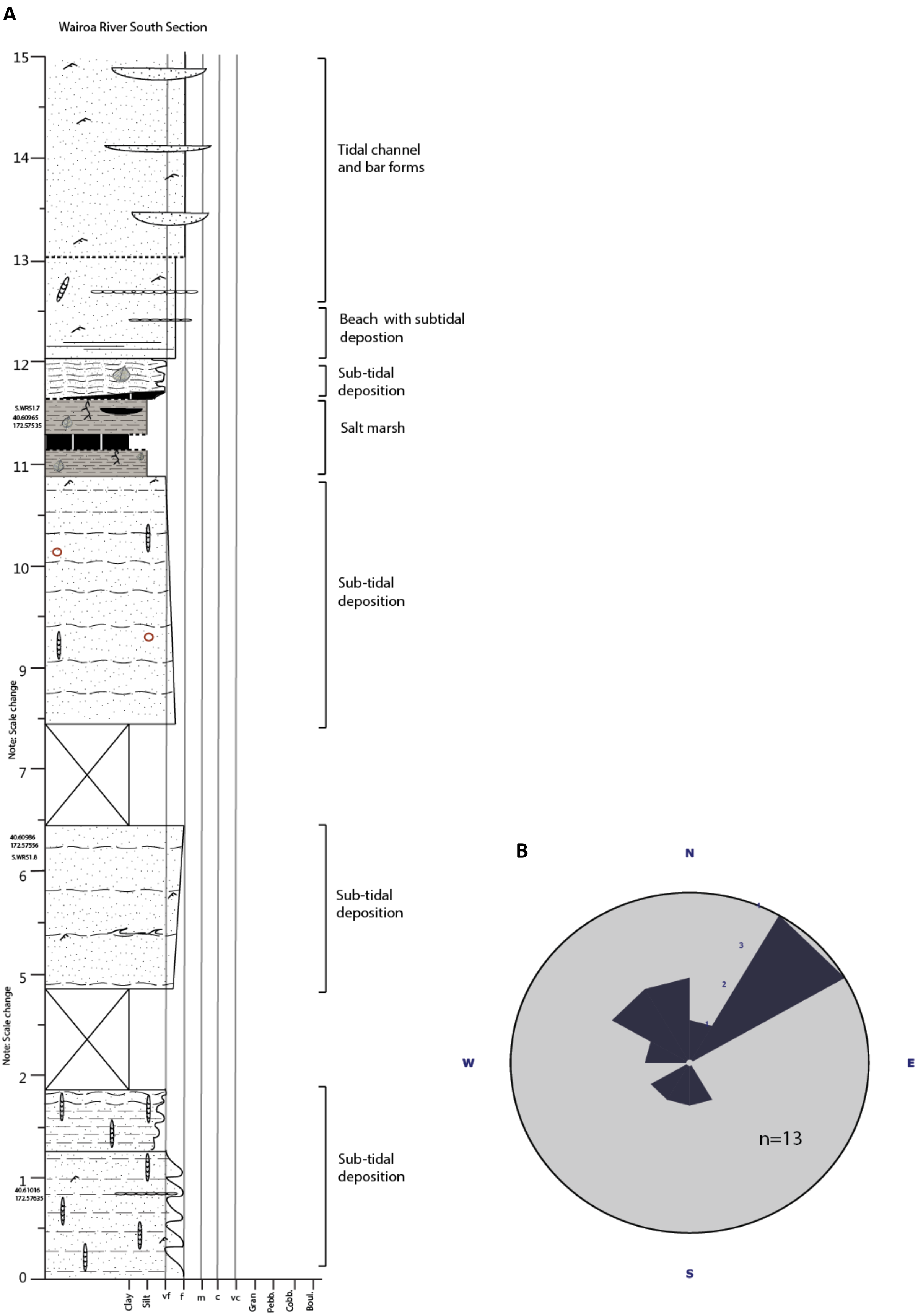


Figure 2.21 – A) Stratigraphic section for the base of the Wairoa River South section; **B)** Paleocurrent data for both the Wairoa River North and South sections.

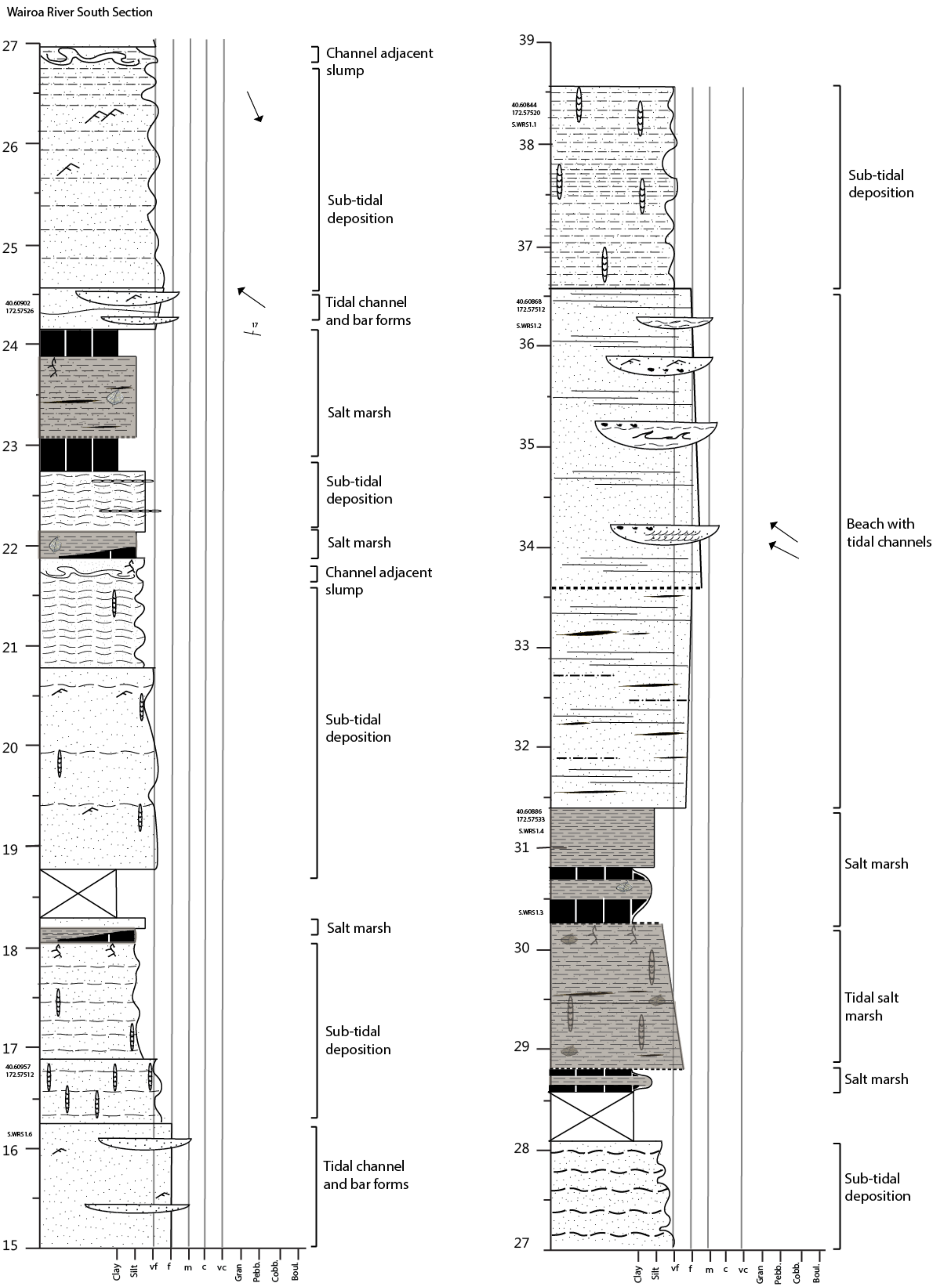


Figure 2.22 – Wairoa River South stratigraphic section.

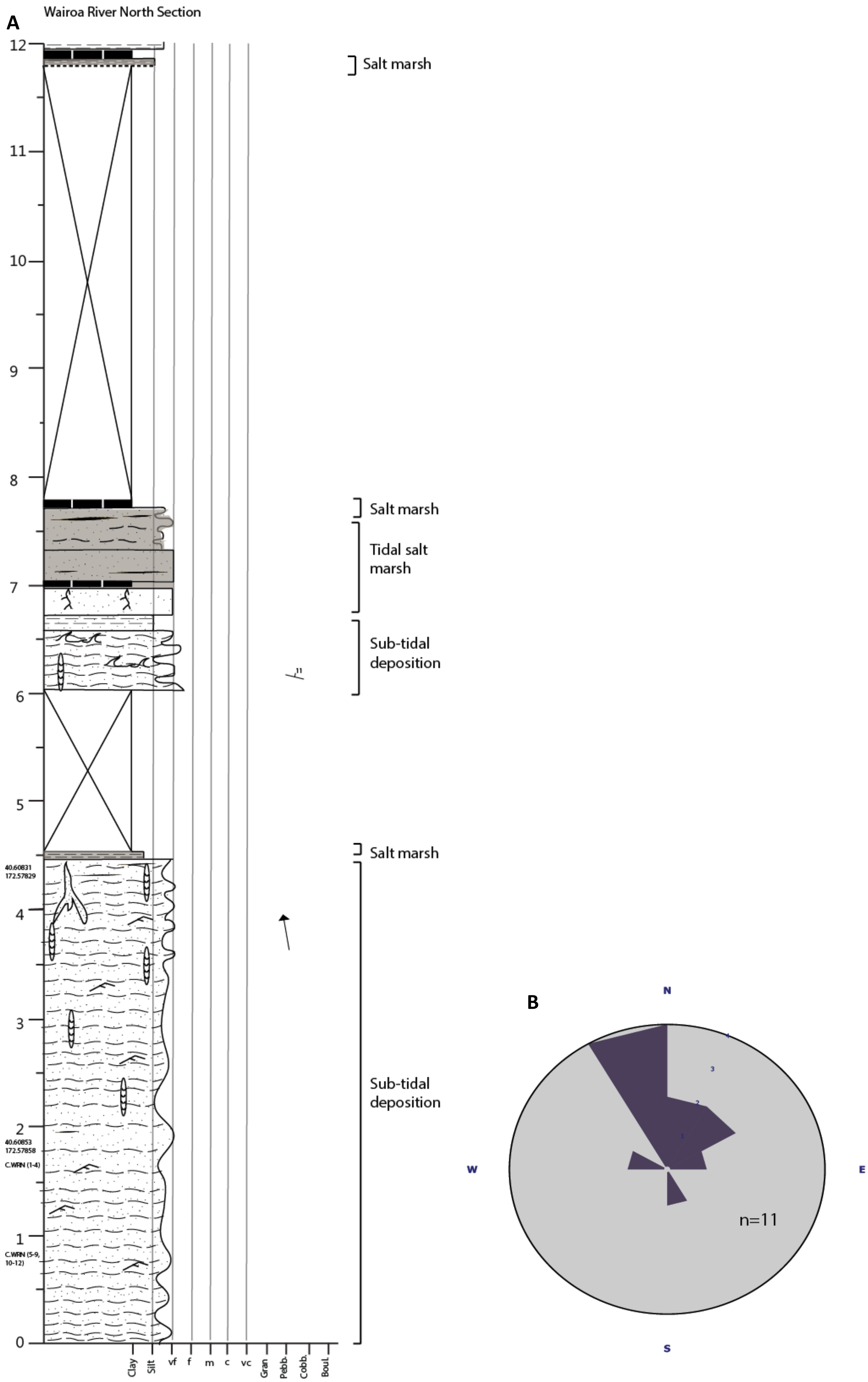


Figure 2.23 – A) Base of the Wairoa River North stratigraphic section. **B)** Paleocurrent data for the Muddy Creek section, (Figure 2.25).

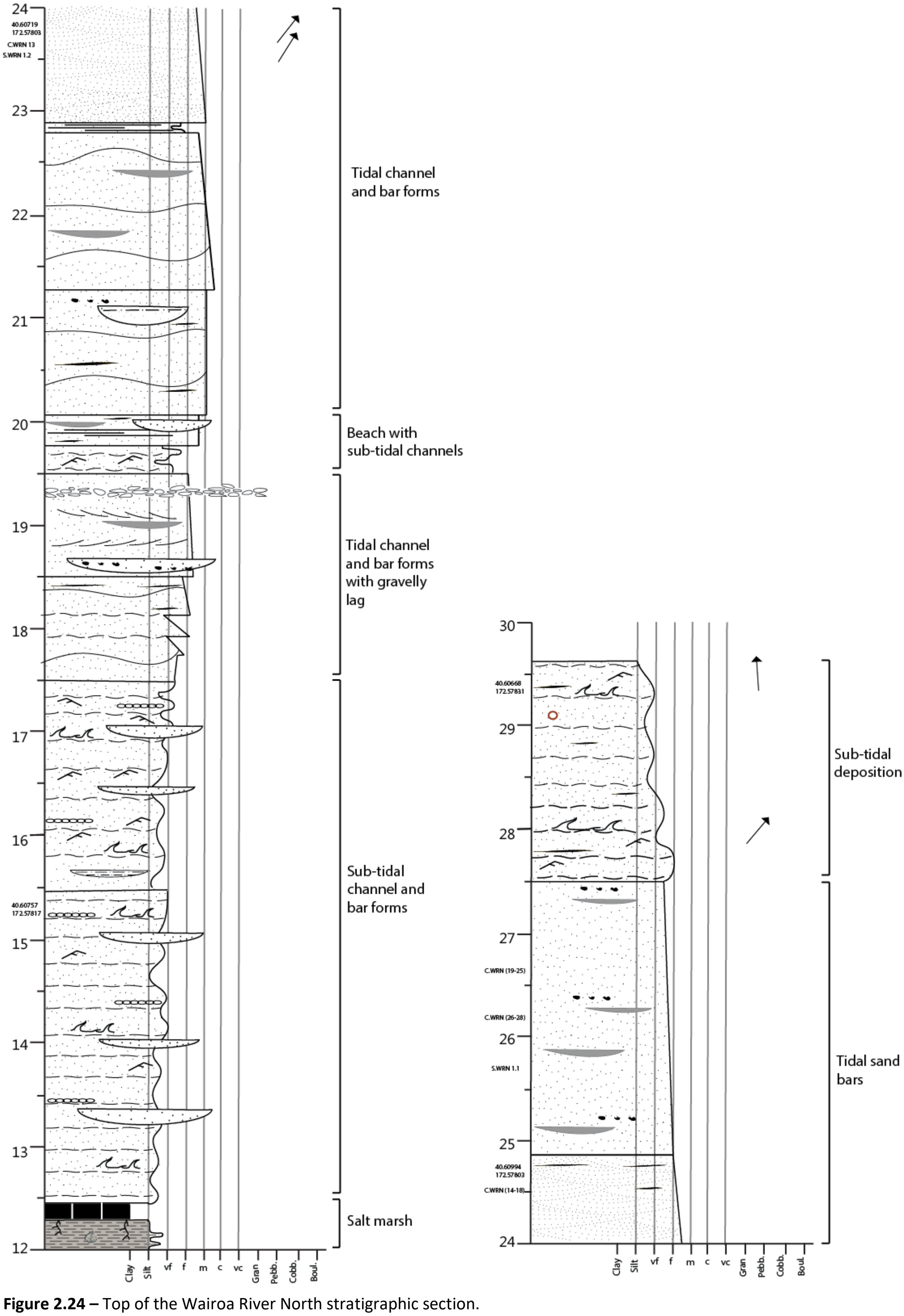


Figure 2.24 – Top of the Wairoa River North stratigraphic section.

Muddy Creek Section

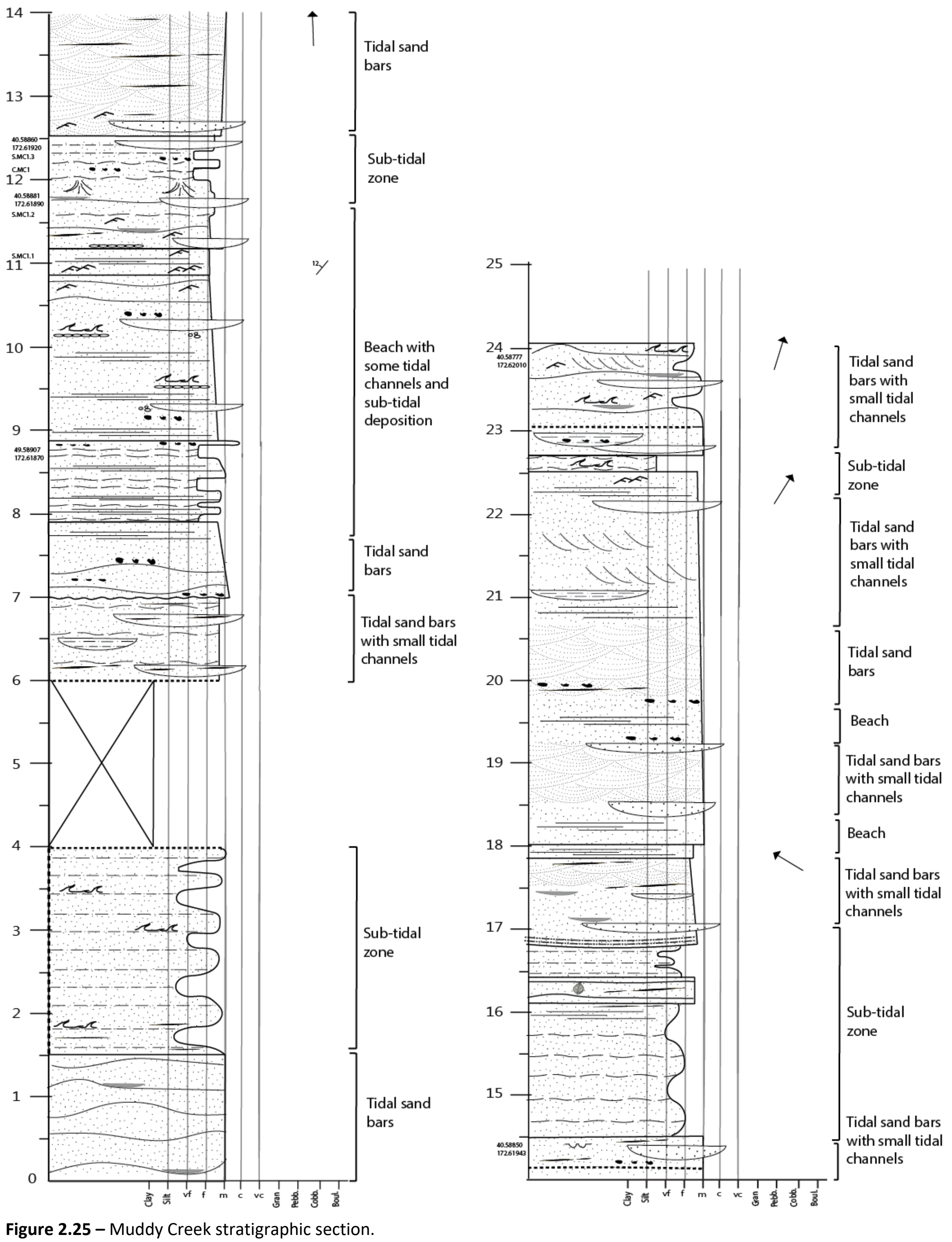


Figure 2.25 – Muddy Creek stratigraphic section.

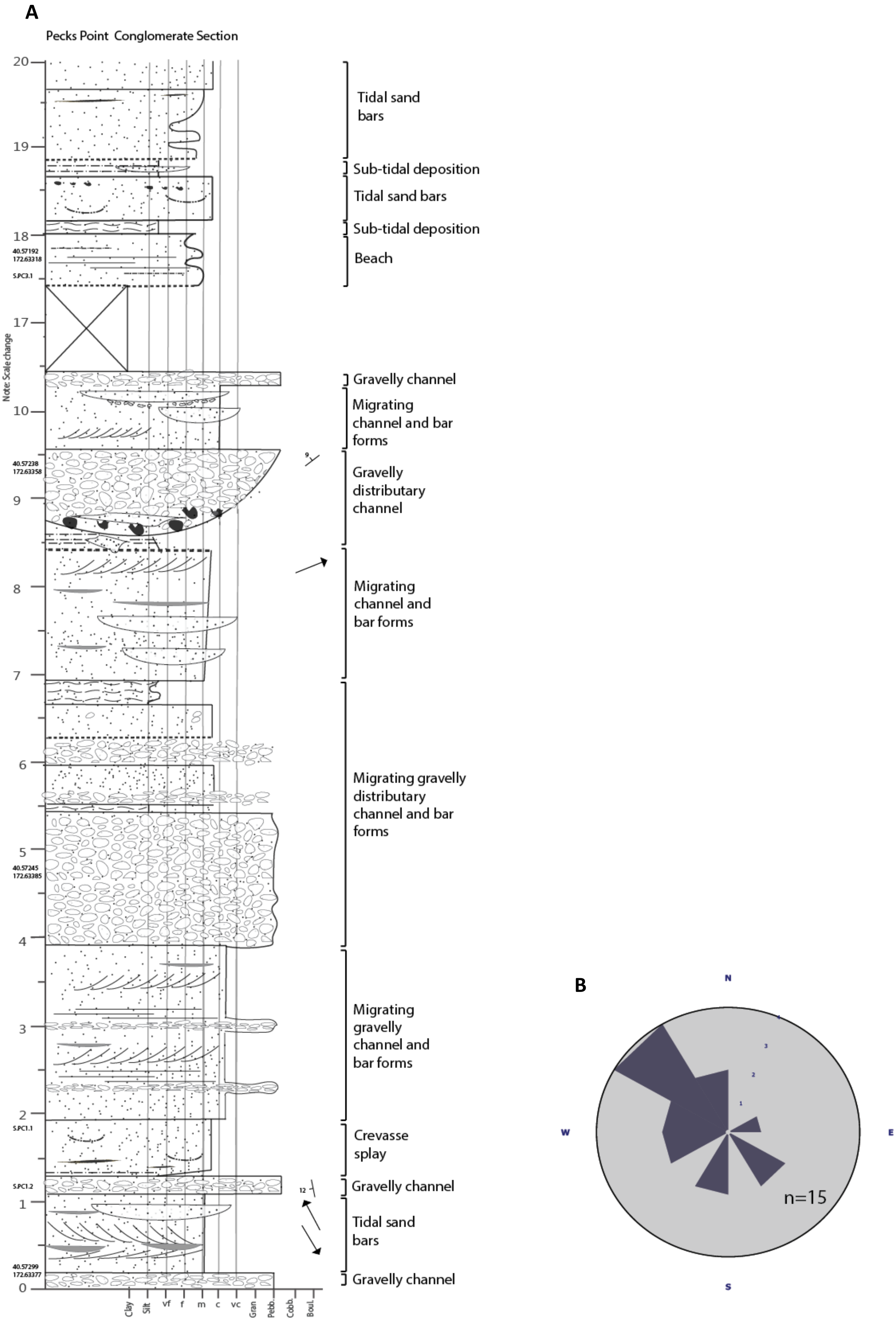


Figure 2.26 – A) Base of the Pecks Point Cgl stratigraphic section. **B)** Paleocurrent data for the Pecks Point Cgl section.

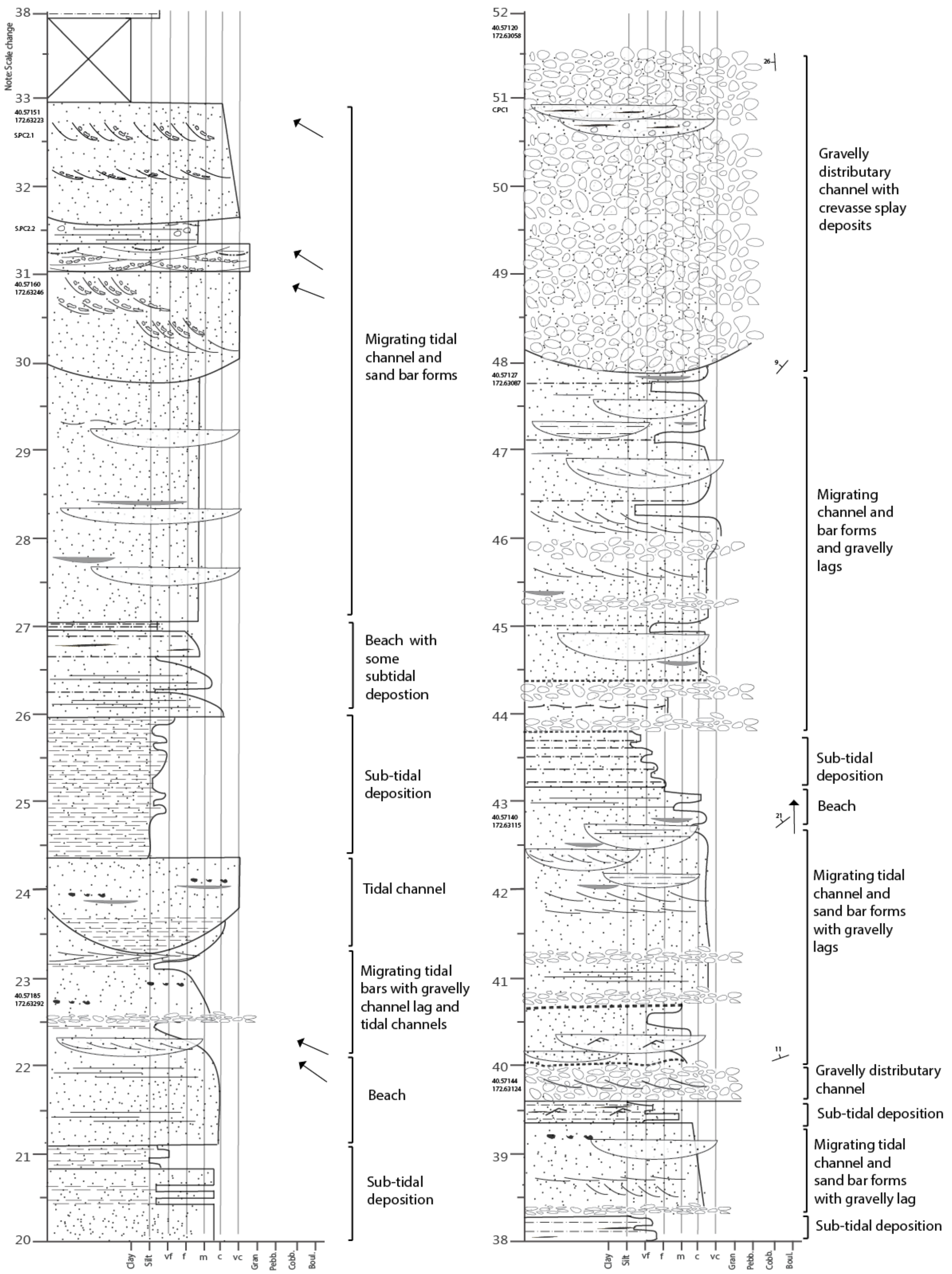


Figure 2.27 – Top of the Pecks Point Cgl stratigraphic section.

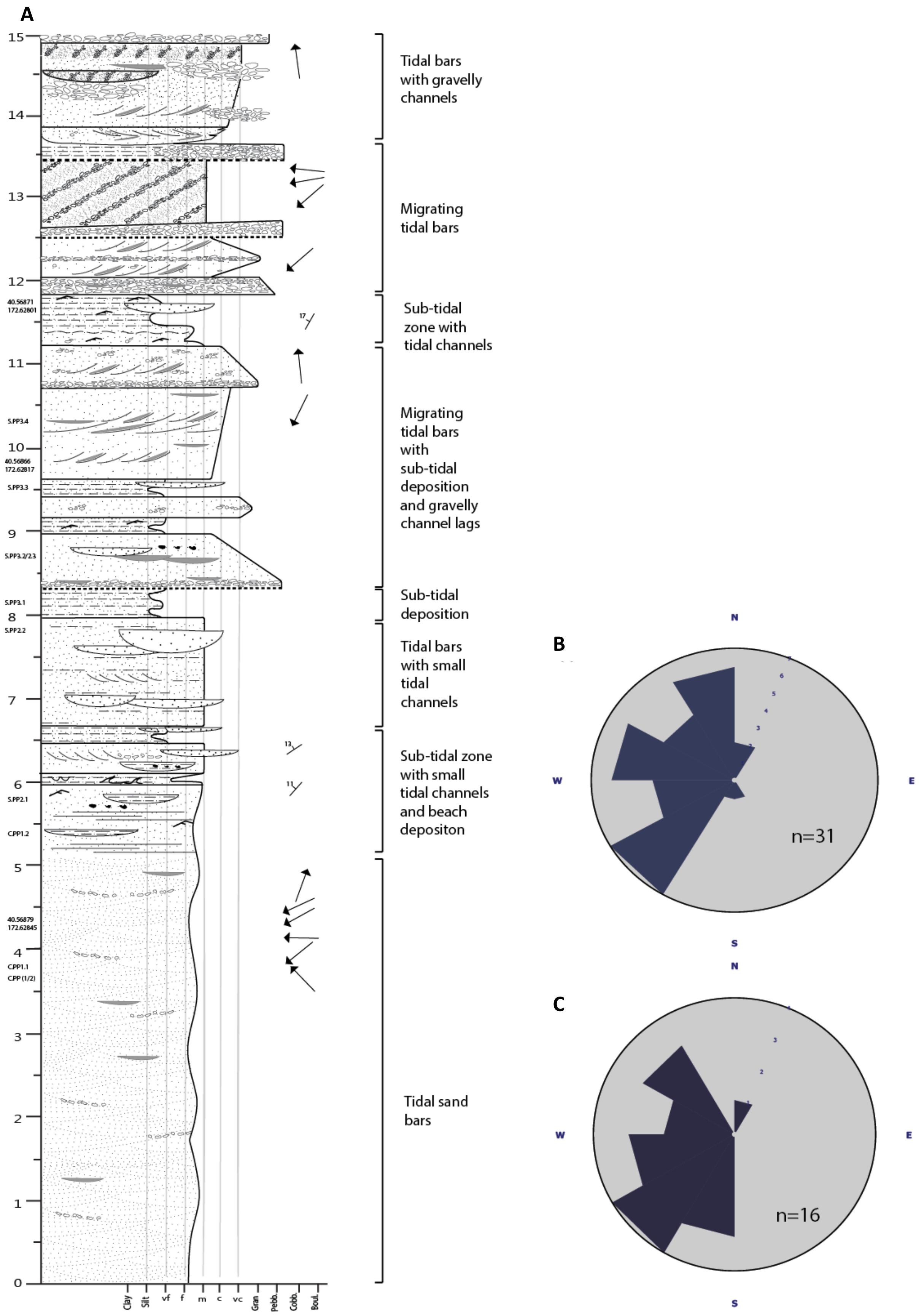


Figure 2.28 A) Base of the Pecks Point North stratigraphic section; **B)** Paleocurrent data for the Pecks Point North section; **C)** Paleocurrent data for the coalified wood fragments measured at Pecks Point North.

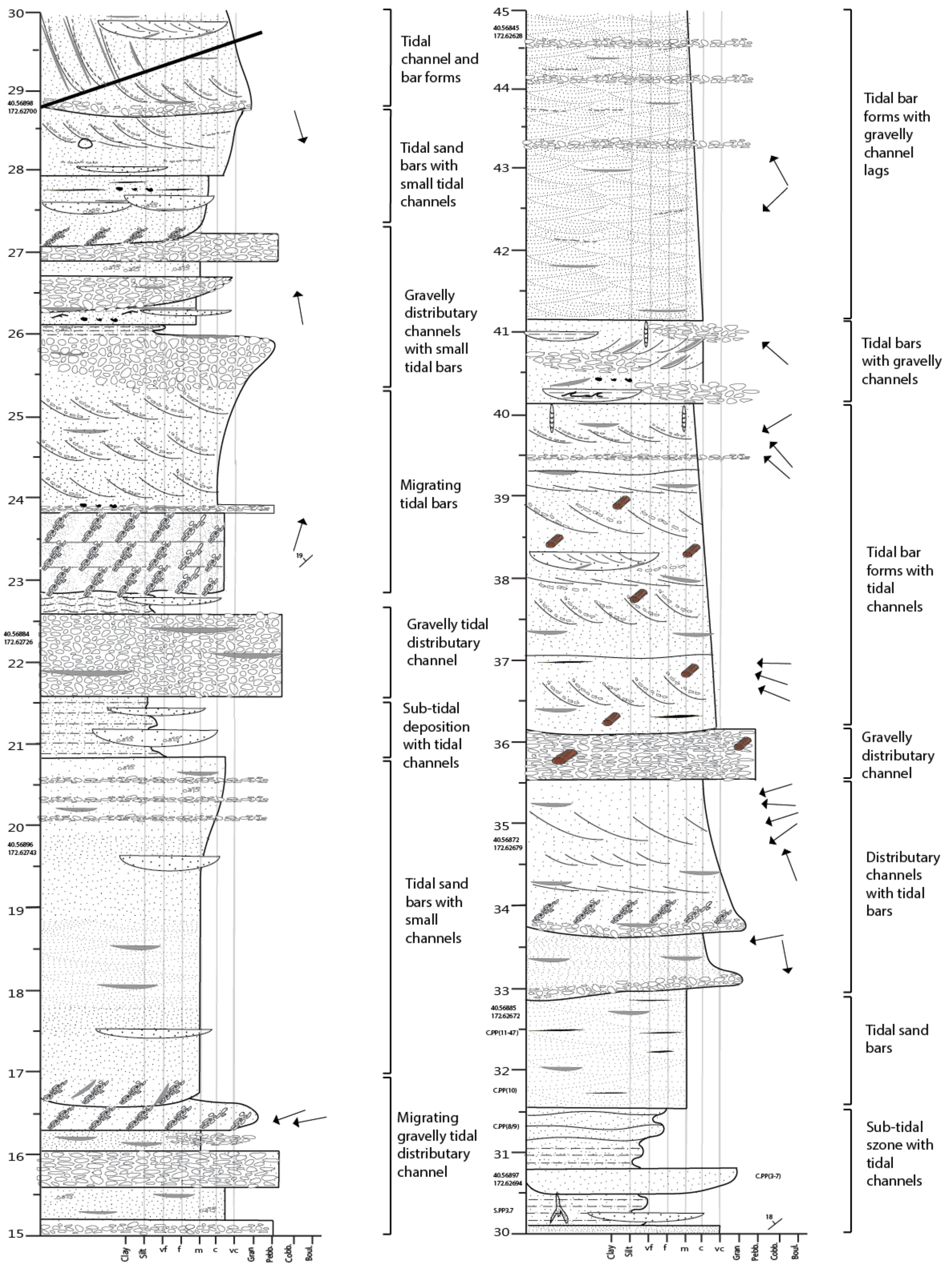


Figure 2.29 – Top of the Pecks Point North stratigraphic section.

2.5 – Discussion

The distribution of measured outcrop has established 10 distinct sedimentary facies within the onshore expression of the North Cape Formation. The relationship between these has revealed distinct lateral variability in sedimentary patterns and depositional settings across the region.

The sedimentary structures within these lithofacies lead to interpretations of depositional settings that can be combined to reflect a broader scale estuarine environment. The interpretation of the North Cape Formation in the field area representing an estuary is not new, but the consideration of how these lithofacies interact and local changes in depositional setting have been neglected in previous works. Therefore, the high-detail sedimentological descriptions described above can be used to define more localised depositional processes within a larger estuarine setting.

There is clear tidal influence throughout the North Cape Formation, in the study area, with numerous occurrences of double mud drapes, diagnostic Ichnofacies, bi-directional crossbed and ripple structures and flaser bedding. It is also important to acknowledge that the majority of lithofacies present within the study area show some evidence for interaction with channel processes at various scales. **Hl, Sp, Sw, Sxt, Sxp** and **G** lithofacies either contain structures that reflect varying channel forms or are channels themselves. **DHl** and **CS** lithofacies are inferred to represent channel adjacent deposits, so too are directly influenced by channel processes.

An overall trend of sediments coarsening from the central region upwards stratigraphically to the north and again to the south can be observed across measured sections. The northeastern sections are characterised by thick, crossbedded sandstones and conglomerates with minor fine grained sandstone and siltstone beds. The Pecks Point north sections show considerable evidence for equal fluvial and marine influence, with diagnostic marine trace fossils, bi-directional cross-beds and double mud drapes. Pecks Point CGL section, in addition to Maori Point (Higgs et al., 2010) seem to show switching between dominantly fluvial deposition to mixed tidal-fluvial sedimentation. These sediments are likely to represent the coarse-grained fluviomarine deposits of a bayhead gravelly delta or bayhead fan delta environment.

There is a complete absence of **C** facies from the northeastern region with only limited expressions of **CS** facies. Although these lithofacies are associated with fluvial systems it is likely that these settings are either too closely linked to tidal settings or represent high energy channel environments, where perhaps the coal is forming in adjacent floodplain. In contrast, coarse grained **G** facies are effectively are absent from all localities except those in the northeastern Whanganui Inlet region. The stratigraphic sections measured in this region record a coarse-grained distributary system, sculpted by channel processes, with periodic shifts between fluvial and tidal dominated deposition.

Western outcrops represent the uppermost units of the North Cape Formation and are characterised by well-sorted fine to medium crossbedded sandstones associated with fluvially-dominated deposition. These outcrops are the only expressions of North Cape Formation presented in this study to contain clean, laterally extensive coal seams related to floodplain deposition, without tidal influence. The upper-most sediments of the North Cape Formation outcropping along the western coast record a switch from marginal marine, estuarine deposition at their base to fluvial dominated deposition.

Central sections are distinctly finer grained and tidally dominated, recording localised regressive sequences from tidal channels, sub-tidal flats to beach and salt marsh deposition, where thin coals are interbedded with fine to very fine sandstones and siltstones. Despite representing lower energy environments than those to the north and south, the central region has consistent and high sedimentation rates indicated by biogenic rich units experiencing minimal mixing and maintaining internal structure. This suggests it was not wholly isolated from the distributary environment in the north and/or south of the region, representing an interdistributary bay setting.

Southern units are mixed tidal-fluvial depositional environments, though are dominated by fine to medium grained crossbedded and wavy sandstones, with less frequent siltstone units and some very coarse grained channel forms. The Mangarakau Swamp section records a general fining upward sequence from moderate energy tidal channel, sub-tidal flat regularly alternating with thin beach deposits to salt marsh deposition with silty interbedded coals marking the top of the sequence. This area likely represents an additional, lower energy, distributary system or one much further from its sediment source than the system to the northeast.

2.6 – Conclusion

There is a clear, strong tidal influence on the majority of North Cape Formation deposits in their onshore expressions in NW Nelson. It is important to note that the northeastern region appears to experience shifts between fluvial and tidal dominated deposition, while the uppermost units along the western coast appear to become more fluvially dominated up section. Most expressions of the 10 described sedimentary facies show evidence for sub-aqueous deposition, where even CZ and C lithofacies are either in wet, marshy environments periodically inundated with salt water or adjacent to channels in a floodplain setting.

Sedimentological analyses ultimately reveal a coarse-grained distributary system in the northeastern extent of the study area which is interpreted to represent a local gravelly delta or fan delta at the bayhead position of an estuary. An additional, secondary distributary system in the south, while the central regions are distinctly finer grained, with smaller scale tidal channels consistent with an interdistributary bay environment. These depositional systems represent sub-environments of a greater estuarine setting which will be better understood with paleogeographic reconstruction in the following chapter.

Chapter 3 – Paleogeography

3.1 – Introduction

An important aspect in the characterisation of sedimentary facies within the North Cape Formation is the consideration of regional tectonic and sedimentary evolution of the Pakawau Sub-Basin and the Southern Taranaki Basin. Extensive data sets containing biostratigraphic, bathymetric, paleogeographic maps as well as outcrop data and paleofacies data from seismic stratigraphy and attribute analysis have been compiled and adapted to facilitate the reassessment of the paleogeographic evolution of the Taranaki Basin and the areas surrounding the region (King and Robinson, 1988; King and Thrasher, 1996; Strogen et al., 2011).

King and Robinson (1988) describe the Cretaceous to early Miocene sedimentation in Taranaki Basin as part of an overall transgressive cycle, with some shoreline fluctuations. Terrestrial sediments of the Late Cretaceous were deposited in normal-fault controlled, rapidly subsiding depocentres. The North Cape Formation in particular, reflects a major south-directed transgression towards the end of the Cretaceous, when the sea flooded coastal plains and within fault controlled alluvial valleys producing a network of narrow, interconnected tidal embayments (King and Thrasher, 1996).

The most recent paleogeographic reconstructions of deposition during the Late Cretaceous in the Taranaki Basin are presented in Strogen et al. (2011) (Figure 3.1). From the Late Haumurian to the latest Haumurian (68-66Ma) the North Cape Formation sedimentation fluctuated from coastal plain to shallow marine (inner shelfal) deposition throughout the Taranaki Basin, though fault controls in the Pakawau and Manaia sub-basins resulted in different conditions in these area of the southern Taranaki Basin (Figure 3.1). They interpret the successions to the southwest of the study as coastal plain deposition and those to the northeast of the study area as proximal submarine fans.

The study area itself, the Whanganui Inlet area, is the only onshore expression of the North Cape Formation and contains dominantly tidally influenced sandstones interbedded with coal and localised conglomerates. The North Cape Formation is interpreted as being deposited in an environment that fluctuated between a terrestrial and a marginal marine, estuarine setting (Bal and Lewis, 1994; Wizevich, 1994; Higgs et al., 2010).

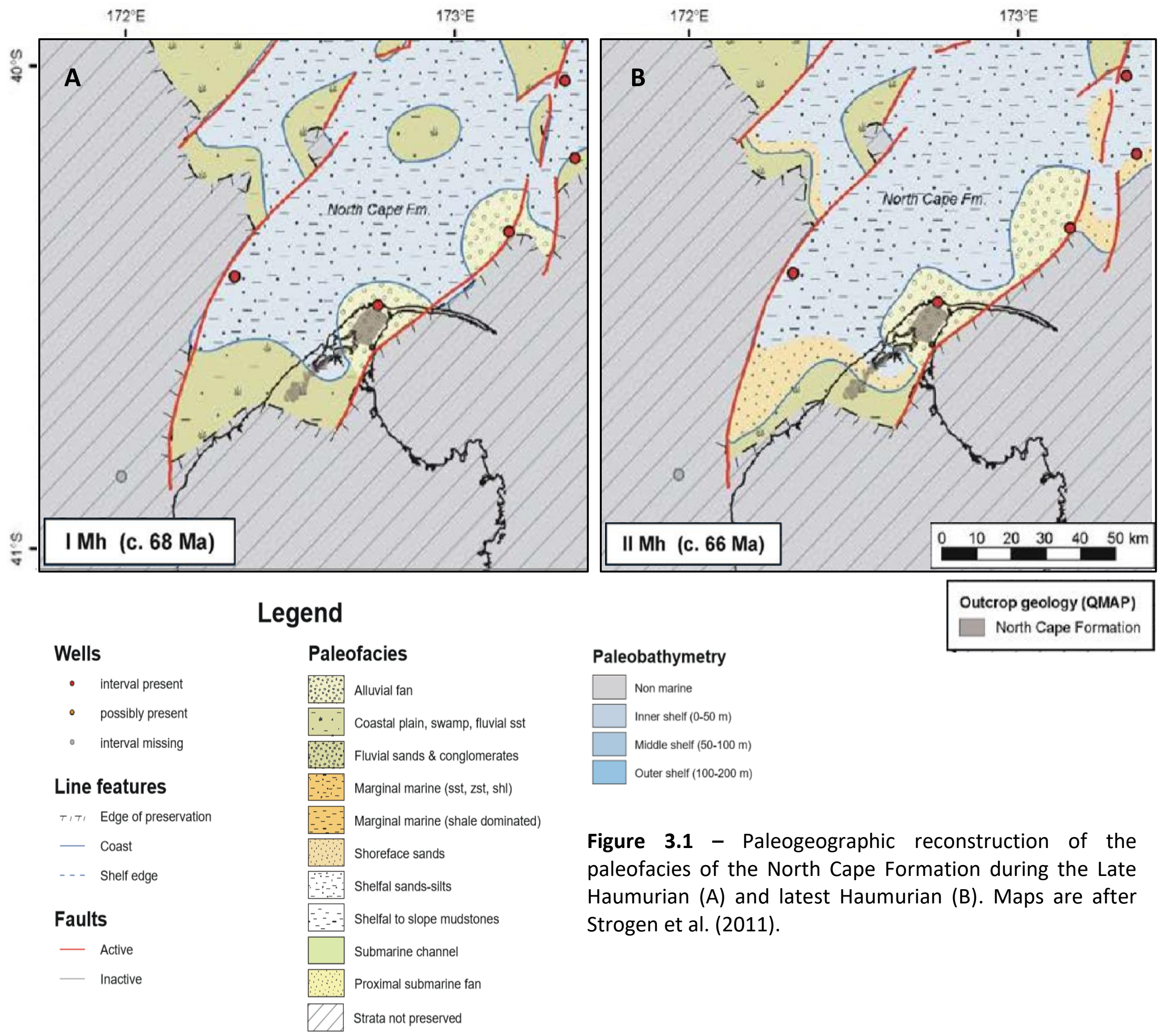


Figure 3.1 – Paleogeographic reconstruction of the paleofacies of the North Cape Formation during the Late Haumurian (A) and latest Haumurian (B). Maps are after Strogen et al. (2011).

Higgs et al. (2010) present the most recent interpretation of lithofacies associations within this onshore expression, where three distinct associations are described following the stratigraphic framework of Bal and Lewis (1994) and Wizevich (1994), Table 3.1. A1 is interpreted as estuary tidal channels, sand shoals and fan deltas; A2 is interpreted as tidal mudflats, salt marshes and mires; and A3 is interpreted as upper delta plain.

Higgs et al. (2010) show that lithofacies A1 is most common in the northern and western parts of the Whanganui Inlet, comprising 15-20% of the North Cape Formation in measured section. Sedimentary structures and trace fossil assemblages indicate deposition within a tidal setting, with well formed, large scale (>2m thickness) channel systems. This association was inferred to represent fan-delta deposition, with sediments likely derived from a local, probably fault-related, uplifted region adjacent to the depositional centre.

Table 3.1 - Lithofacies characteristics and inferred depositional setting of the North Cape Formation, onshore NW Nelson after Higgs et al. (2010) .

Lithofacies	Sedimentary Structures	Inferred Depositional Setting
A1	Metre-scale bedding; bi-directional and herringbone cross-bedding; tidal bundels; sand waves; reactivation surfaces; nested trough and stacked tabular cross-beds; climbing ripples	*Tidally Influenced:* Tidal channels and intertidal sand shoals; local fan deltas
A2	Decimetre-scale beds; small channels; rhythmic bedding, micro-ripples; bioturbation; small rootlets; micro faulting/slumping	*Tidal Mudflats:* Intertidal and supratidal mud and sand flats; salt marshes and mires
A3	Metre-scale beds; alternating sandstone/siltstone units; fining and coarsening upward beds; wavy lamination; thickening upward cycles; well-developed channel forms; sheet beds; large rootlets; quasi-liquid deformation	*Upper Delta Plain:* Distributary/crevasse channel splays; levees, mouth bars into freshwater bays; mires

Lithofacies A2 occurs in both the south and west of the Whanganui Inlet and comprises 35-40% of the North Cape Formation outcrop in sections (Higgs et al., 2010). Diagnostic rhythmic bedding and overall low sand content lead these authors to the interpretation of an intertidal and supra tidal mudflat with thin, poorly developed coal seams indicating salt marsh and paralic mire deposition, Occasional lenticular sandstones representing small tidal channels crosscut adjacent strata.

Lithofacies A3 is characterised by wavy sandstone, mudstone and coal seams and forms 40-45% of the North Cape Formation outcrop (Higgs et al., 2010). This grouping was identified predominantly along the western coast of the Whanganui Inlet and in limited locations in the south. These units contain well-developed channel forms, mires and are devoid of tidal signatures. As such they are interpreted as upper delta plain deposits.

Previously established lithofacies associations provide the framework for my study on detailed lateral facies changes and paleogeographic reconstruction of the estuarine setting the North Cape Formation was deposited in.

3.2 – Methods

Detailed sedimentological facies descriptions were developed (Chapter 2) and grouped in order to characterise the depositional systems that produced them; these are referred to as lithofacies associations. There is some overlap between facies associations, thus some lithofacies are assigned to more than one association or have variations that define different depositional processes or settings indicative of a different association. This is because the interpreted depositional environments have many of the same processes operating in them and occur laterally to each other.

Following this approach the interpreted depositional settings were mapped relative to their position in the Whanganui Inlet's present form. Paleoflow measurements were collected to establish dominant flow directions as an aid to reconstructing the paleodepositional environments of the North Cape Formation in outcrop.

3.3 – Lithofacies Associations:

Facies associations are the combination of closely related facies "genetically related to one another and which have some environmental significance" (Collinson, 1969). These can also be considered as architectural elements, implying they represent the building block to interpreting a specific depositional environment. When considering these facies associations as architectural elements it becomes clear that some depositional systems contain universally occurring elements (Walker, 1992), allowing a broader range of interpretations and thus resulting in some of the overlap of the lithofacies found in the North Cape Formation.

Following similar facies groupings to those proposed initially by Bal (1992)and further developed in Bal and Lewis (1994) and Higgs et al. (2010) I have noted three overriding lithofacies associations for the onshore units of the North Cape Formation, in northwest Nelson area. These are defined by their dominant mode of deposition:

The associations are:

DP – Delta Plain, distributary channel environment - comprising sandy, fluvially dominated sediments with local floodplain deposition. Recognised by conglomerate **(G)**, crossbedded sandstone **(Sxt, Sxp)** wavy bedded sandstone **(Sw)**, planar laminated sandstone **(Sp)** , carbonaceous sandstone **(CS)** and freshwater coal **(C)** lithofacies (Chapter 2).

DF – Tidally influenced Delta Front environment - comprising heterolithic, mixed fluvial and tidal processes. Recognised by crossbedded sandstone **(Sxt, Sxp),** wavy bedded sandstone **(Sw)** planar laminated sandstone **(Sp)** and heterolithic sandstone **(Hl, DHl)**, with rare conglomerate **(G)** lithofacies (Chapter 2).

ST – Sub-tidal environment - dominated by tidal processes, with little to no fluvial influence. Recognised by wavy bedded sandstone **(Sw)** planar laminated sandstone **(Sp),** heterolithic sandstone **(Hl, DHl)** and marine influenced carbonaceous siltstone **(Zb)** and silty coal **(CZ)** lithofacies (Chapter 2).

Table 3.2 – Lithofacies associations established for the North Cape Formation and the lithofacies that comprise them.

<table>
<tr><th rowspan="2">Lithofacies Code</th><th rowspan="2">CZ</th><th rowspan="2">Zb</th><th rowspan="2">Hl</th><th rowspan="2">DHl</th><th rowspan="2">Sp</th><th rowspan="2">Sw</th><th>Sxt</th><th>Sxp</th><th rowspan="2">G</th><th rowspan="2">CS</th><th rowspan="2">C</th></tr>
<tr><th colspan="2">Cross-bedded sandstone</th></tr>
<tr><td>Lithofacies Description</td><td>Silty coal</td><td>Carbonaceous bioturbated siltstone</td><td>Thinly interbedded heterolithic sandstone</td><td>Deformed heterolithic siltstone</td><td>Planar laminated sandstone</td><td>Massive to wavy bedded sandstone</td><td>Trough</td><td>Planar Tabular</td><td>Conglomerates</td><td>Carbonaceous sandstone</td><td>Coal</td></tr>
<tr><td rowspan="3">Lithofacies Association</td><td colspan="4"></td><td colspan="7">DP</td></tr>
<tr><td colspan="2"></td><td colspan="7">DF</td><td colspan="2"></td></tr>
<tr><td colspan="6">ST</td><td colspan="5"></td></tr>
</table>

Facies Association DP: Delta plain environment

The lithofacies within Association DP are sandstone and gravel dominated, varying in grain size across their distribution in the present day outcrop, and comprising 26% of measured outcrops examined in this study. Local conglomerates (**lithofacies G**) and wavy and cross-bedded medium sandstones **(Sxt, Sw, Sxp)** define the north eastern outcrops while wavy and cross-bedded fine to medium sandstones **(Sxt, Sw, Sxp)** form the majority of the western outcrop area. Unidirectional sedimentary structures define the Delta Plain Lithofacies. Moderate to high energy trough and planar tabular cross-beds, are common in the sandstone units with individual sets ranging from decimetre to metre scale thickness. The characteristic **G**, **Sxt**, **Sw** and **Sxp** lithofacies occur in metre-scale beds which often display sharp, erosional bases with channel forms. Thin **Sp** lithofacies interbeds (centimetre scale) also occur, alongside abundant organic stringers and mud draping. There is a notable absence of the paired drapes observed elsewhere.

Organic matter is common throughout the facies within A1 and there is an absence of dinoflagellates and marine trace fossils. Dark, organic rich very-fine sandstones **(CS)**, clean, decimetre thick coal seams **(C)** with well-developed root traces are characteristic of local fining upward successionss in the western portion of the study area.

The lithofacies that comprise the Delta Plain Lithofacies Association (DP) all indicate fluvial deposition with a notable absence of the tidal signatures observed in the other Lithofacies

Associations. Deposits are interpreted to include both braided and meandering distributary channels, channel associated bar forms and crevasse splays in addition to local fresh water peat swamps. Lithofacies Association DP is therefore assigned to the delta plain environment. Lithofacies DP is observed to alternate with the tidally influenced Delta Front Lithofacies Association (DF) so is assumed to be positioned landward of a tidally dominated estuarine setting. The western outcrops that represent the upper North Cape Formation successions are finer grained than those along the eastern coastal outcrops, averaging fine sandstones with an absence of conglomerate lithofacies. These outcrops contain the only expressions of freshwater coal lithofacies and are considered lower energy delta plain deposits with floodplain deposition of crevasse splays and local peat swamps. Coal analyses from equivalent lithofacies published in Bal (1992) indicate that the coals of Lithofacies DP were deposited in swamps that were very wet, poorly oxygenated and in low lying environments, supporting the interpretation of floodplain deposition within a delta plain environment.

Facies Association A2: Tidally influenced Delta Front environment:

Generally the lithofacies within the tidally influenced Delta Front association (DF) comprise 55% of the measured outcrop in the study area. They are fine-medium sandstones, characterised by trough cross-beds and current-ripple laminations separated by abundant mud drapes, with many displaying paired drapes. Sandstone units **(Sxt, Sw)** commonly display sharp, erosional bases with some lens-shaped beds and are interbedded with heterolithic units **(Hl)** comprised of cyclic bedding. Wavy and cross-bedded sandstones **(Sw, Sxt)** with occasional alternations of planar laminated sandstones **(Sp)** lithofacies dominate the depositional settings. Conglomerate **(G)** lithofacies are rare in the tidally influenced Delta Front association (DF) and are only present in the northeastern outcrop. Paleocurrent measurements typically suggest a dominant basinward flow to the northwest although cross-bed sets alternate direction and are common and well-developed. Lithofacies within Association DF contain diagnostic fauna indicative of sub-tidal to shallow marine environments, similar Ichnofacies are observed in Pliocene shallow marine to sub-tidal estuarine deposits of the Quinault Formation, Washington (Campbell, 2000).

The facies that comprise Lithofacies Association DF record a mixed fluvial and tidal depositional setting. Despite having similar sedimentary facies as in association DP the dominant fluvial sedimentary processes shows evidence for strong tidal overprinting. Additionally a general reduction in grain size suggests the depositional environments represent lower energy depositional processes than the delta plain environment (DP) described previously. Instead association DF is interpreted as a delta front environment, with tidally modulated bar forms in both terminal distributary and tidal channels. The presence of tidal bundles within heterolithic interbeds **(Hl)** and common paired mud drapes in wavy and cross-bedded sandstones **(Sw, Sxt)** and beds all support an interpretation of strong tidal influence. Similarly, the biogenic evidence for marine fauna indicates a more seaward depositional environment than that of Association DP. The preservation of sedimentary structure within facies with considerable biogenic evidence and the presence of climbing-ripple laminations, soft sediment deformation and occasional preservation of topsets in **Sxt** beds suggest the overall depositional setting of the North Cape Formation maintained a relatively high sedimentation rate through the Late Cretaceous in the Pakawau Basin (cf. Olariu and Bhattacharya (2006)).

Overall it is difficult to assign a dominant depositional process as both tidal and fluvial processes appear ultimately equal in their role in developing the depositional settings of a delta front environment. Fluvial signatures are clear based on the presence of high energy distributary channels, with cross-bedding of varying scale. The influence of wave action is interpreted to be minimal, if not non-existent due to the lack of associated sedimentary structures and textures.

Facies Association A3: Sub-tidal environment.

The facies that comprise the Sub-tidal Lithofacies Association (ST) comprise only 19% of the measured outcrop and are notably finer grained than Associations DP and DF. ST is instead dominated by moderately sorted deposits of siltstone and very-fine grained sandstones of silty coal **(CZ)**, carbonaceous siltstone **(Zb)**, heterolithic sandstone **(DHl, Hl)**, planar laminated and wavy bedded sandstones **(Sp, Sw)** lithofacies. Beds are typically decimetre scale and contain distinct tidal signatures, such as flaser and lenticular bedding and brackish trace fossil assemblages. While the major stratigraphic beds are not commonly lens-shaped it is common for smaller-scale channel forms of varying scale to cut through most lithofacies. The heterolithic interbedded sandstone lithofacies **(Hl, DHl)** record cyclic alternations of sandstone and siltstone with some displaying clear evidence for bi-directional currents as shown by current ripple laminations by flaser bedding, indicating inter-tidal sedimentation. Soft-sediment deformation structures characterise **DHl** lithofacies, and are exhibited in **Hl** facies, with biogenic loading structures exclusive to these lithofacies. Wavy bedded sandstone **(Sw)** and minor cross-bedded sandstone **(Sxt)** lithofacies in the Sub-tidal Lithofacies Association (ST) are fine- to medium-grained sandstones and are notably thinner with scours and cross beds sets smaller and less well-formed than those that characterise the other two Lithofacies Associations. Locally, organic rich bioturbated siltstone **(Zb)** and silty coal **(CZ)** lithofacies alternate and are bioturbated by small root traces and occasional fossil traces.

The sedimentary structures observed in the lithofacies that comprise the Sub-tidal Lithofacies Association (ST) record cyclic alternation of current ripple forms in the lower-flow regime to upper plane-bed flow and decimetre-scale crude dune forms (Reineck and Singh, 1980; Dalrymple et al., 1992; Aschoff et al., 2016).The presence of frequent channels cutting through lithofacies suggest tidal channels of varying scale meandered through the area. The incidence of soft-sediment deformation structures and the preservation of biogenic loading structures in **DHl** and **Hl** lithofacies suggest the depositional setting was consistently wet and represents a sub-tidal estuary floor environment. The relationship between **Zb** and **CZ** facies indicate in situ, vegetation growth. Geochemical analyses on equivalent **CZ** lithofacies presented in Bal (1992) shows that these thin coals were deposited in a low lying, wet marsh influenced by brackish water during its deposition. The alternation of these lithofacies with sub-tidal sand flat deposition suggest the environment experienced changes from sub-tidal to supra-tidal salt marsh environments. Ultimately the lithofacies relationships reflect an environment that passed from sub-tidal channels in an estuary to marginal tidal flats and local salt marshes.

Ultimately the facies that comprise the Sub-tidal Lithofacies Association all record sub-aqueous deposition with the best developed evidence for tidal deposition of the three lithofacies assigned to the North Cape Formation in the study area.

3.4 – Discussion

3.4.1 - The North Cape Formation depositional systems:

The definition of estuaries is often gauged by relative salinity and trace fossil assemblages but for the purpose of application to the units of the North Cape Formation this study considers the classification of (Dalrymple et al., 1992), where an estuary is a flooded valley on a transgressive shoreline that receives sediment from both marine and non-marine sources and the facies that comprise them are controlled by the relative role of fluvial, tidal and wave processes. Typically estuaries contain a mix of each of these primary sedimentary transport processes, with their roles changing based on location within an estuary and with changes to local topography. As a result the distribution and character of facies in an estuarine setting are expected to show marked variability (Aschoff et al., 2016).

The thorough analysis of sedimentary facies of the North Cape Formation outcrop presented in Chapter 2 show that wave-influence was minimal during deposition, with units devoid of coarse shelly material and lacking very well-sorted beach deposits. As such the depositional environment for the outcropping North Cape Formation during the Late Cretaceous is interpreted as that of a sandy mixed fluvio-tidal estuary setting, ultimately lacking a local barrier.

The western extent of the study area represent the uppermost outcropping successions of the North Cape Formation and are dominated by lithofacies that comprise the delta plain environment of Lithofacies Association DP, interpreted as more fluvial in character. These outcrops contain the thickest and cleanest expressions of coal (**C**) lithofacies, which indicate freshwater, peat bog deposition in a low-lying coastal plain. These deposits are adjacent to low-moderate energy channelised sandstone lithofacies with abundant organic matter and no obvious tidal signatures, support the interpretation that meandering fluvial deposition dominated the later stages of North Cape deposition.

Along the northeastern coast of the Whanganui Inlet the North Cape Formation is distinctly coarser grained, with conglomerates and on average medium grained sandstone facies. These facies are interpreted to represent a Delta Plain Lithofacies Association (DP) which experienced shifts towards a mixed fluvial-tidal environment at the head of an estuary. Paleocurrent data show a dominant north to northwest trend which suggests sediment was fed off the Whakamarama Fault in the east of this outcrop location with flow directed basinward.

Successions deposited seaward (west) of the northeastern study area represent the Tidal Delta Front Lithofacies Association (DF) contain evidence of fluvial deposition with well-developed tidal signatures; with bi-directional cross-bedding separated by mud drapes and flaser bedding, diagnostic dinoflagellates and marine trace fossil assemblages. Net sediment transport was to the northwest, with an ultimately unidirectional paleoflow with more subtle alternating directions from tidal overprinting recognised in some cross-bedded units. Interpretation of these lithofacies representing a tidally influenced delta front environment is consistent with the tidal bay-head delta environment at the head of a mixed-energy estuary such as the modern Gironde Estuary, SW France (Dalrymple and Choi, 2007; Aschoff et al., 2016). This setting reflects a combination of fluvial and tidal processes with common cross-strata, flaser bedding and cross-strata with frequent mud rip-up clasts (Dalrymple and Choi, 2007; Tessier, 2010; Aschoff et al., 2016). Aschoff et al. (2016) describe the common defining feature of bayhead deltas in the rock record as basinward directed paleocurrents generated by mainly fluvial processes and strongly overprinted by tides. Brackish trace and body fossils are often recognised in deposits with paired mud drapes also prevalent. Bayhead deltas represent the sedimentary system that forms at the head of an estuary where sediment-laden fresh waters enter brackish bay waters and is interpreted to be the depositional setting in which the northeastern successions of the Delta Front Lithofacies Association (DF) in the North Cape Formation were deposited.

Previous interpretations (Bal, 1992; Bal and Lewis, 1994; Higgs et al., 2010) of the depositional settings for the North Cape Formation place local fan deltas in place of the bayhead fan delta environment suggested in this study. Fan deltas are considered to be applied to all 'wet' and 'dry' varieties of alluvial fan, and although it is important for these to have close proximity to highlands and tectonic escarpments it may not necessarily be critical for applying a fan delta definition. instead the lithofacies characteristics are considered the most important criteria for recognition (Nemec and Steel, 1988). The North Cape Formation was deposited in relatively close proximity to the Whakamarama Fault (<10km), with sediment clearly being fed off this and into the head of an estuary environment. The lateral relationship of the Delta Front Lithofacies Association (DF) with interpreted local sheltered embayments and lagoonal environments characterised by the Sub-tidal Lithofacies Association (ST) suggests that these systems were separated by smaller embayments and within a greater estuarine environment that produced bayhead fan delta deposition in the northeastern region.

The frequent alternations between delta plain and delta front deposition in the northeastern region of the study area are expected to reflect local fluctuations in the position of the shoreline or delta switching, where fluvial dominated deposition represents low tidal range and/or a more headward position along the delta plain. A second, lower energy, fluvial system is by the lithofacies present in the southern sections, cross-bedded and wavy bedded sandstone **(Sxt, Sw)**, planar laminated **(Sp)** and heterolithic interbedded sandstone **(Hl)**, where tidal influence and minor wave action result in reworked deposits. These deposits show decimetre scale trough cross-bed sets and common silt rip-up clasts and are also interpreted to represent the tidal Delta Front Association (DF) with paleocurrent measurements indicating dominantly northward flow.

The present day eastern coastline of New Zealand's Golden Bay region displays sand dominated deposition with no wave barriers and deposition fed by successive local deltas. With no offshore barrier these environments are exposed to considerable wave action. The present day geometry of the Whanganui Inlet on Nelson's northwest coats has created a sheltered estuary that is considerably more mud and silt dominated than the open eastern coastline. With progression down the eastern coast of Nelson smaller enclosed bays with well-developed sand barriers produce more muddy deposits at the head of the embayment. There is a well-developed barrier and sand spit on the seaward side of the Whanganui Inlet with vegetated dune forms and associated barrier beaches that were not observed in the localised North Cape Formation outcrop. It is possible that during the deposition of the North Cape Formation there were small sheltered embayments with lagoonal environments between successive bayhead deltas or river outlets along the eastern coastline without a considerable wave-barrier developed to the west.

Between the mixed fluvio-tidal depositional settings of the Delta Front Lithofacies Association (DF) is the Sub-tidal Lithofacies Association (ST) deposition. The central study area is tidally dominated with no fluvial influence. The interpreted environment is almost entirely sub-aqueous with dominant deposition in a sub-tidal estuarine floor, lagoonal, setting grading into local salt marshes. The lithofacies that comprise this depositional setting have the best developed tidal signatures within the study area, with flaser and lenticular bedding, and abundant, low diversity marine trace fossil assemblages. Lithofacies Association ST shows frequent cross-strata with lens-shapes and tidal structures indicative of tidal channels (e.g. current ripple laminations, rhythmic bedding) (Reineck and Singh, 1980; Weimer et al., 1982; Reinson, 1992). These vary in scale throughout outcrop and are important to recognise in terms of their significance to reservoir potential (Weimer et al., 1982).

Analysis of modern and ancient estuarine environments as discussed in Aschoff et al. (2016) suggest inherited topography plays a role in the evolution of estuarine systems and the resultant facies tracts. This can be applied to the lateral facies changes in the North Cape Formation in the study area. In order to produce low-energy, almost lagoonal deposition of the Sub-tidal Lithofacies Association ST a sheltered embayment must have existed, protecting the depositional system from both wave action and larger tidal channel forms from adjacent bay-head delta and delta front environments (Reinson, 1992). The interpretation of enclosed or sheltered deposition of Lithofacies Association ST suggests that the observed cyclic shifts from salt marsh deposition to sub-tidal, estuary floor deposition may have occurred due to small scale faulting in the region causing local subsidence. An alternative explanation for these cyclic fluctuations to water-levels could be the result of delta switching or delta flooding events; however the interpreted sheltered nature of the depositional environment should effectively eliminate the effect of these events on the lithofacies of the central region of the study area.

It is important to consider the relatively high and consistent sediment input throughout the study area indicated by the preservation of sedimentary structures within all lithofacies, despite strong evidence of bioturbation from vegetation and marine fauna. This suggests that although a main distributary system is present in the northeastern region of the depositional setting a number of smaller scale fluvial and tidal channels were responsible for sediment redistribution throughout the depositional history of the North Cape Formation in the study area.

In general the Lithofacies Associations that characterise the North Cape Formation in the study area are considered to represent laterally adjacent and contemporaneous sub-environments of a larger estuarine environment defined by their relative position from the shoreline. Lithofacies Association DP represents the delta plain environment, where fluvial dominated deposition occurs headward of fluvial-tidal transition recognised in the delta front environment of Lithofacies Association DF. Lithofacies Association ST represents the lower-energy deposition of fine-grained material of the sub-tidal to tidal flat zone adjacent to distributary systems and likely within a sheltered embayment.

A schematic representation of the presumed paleodepositional environments of the North Cape Formation in the study area in addition to the position of the bayhead fan delta environment and the more significant distributary channels is presented in figure 3.2.

3.4.2 – Analogous tide-dominated estuaries

The structure and geometry of the estuarine environment of the North Cape Formation in the study

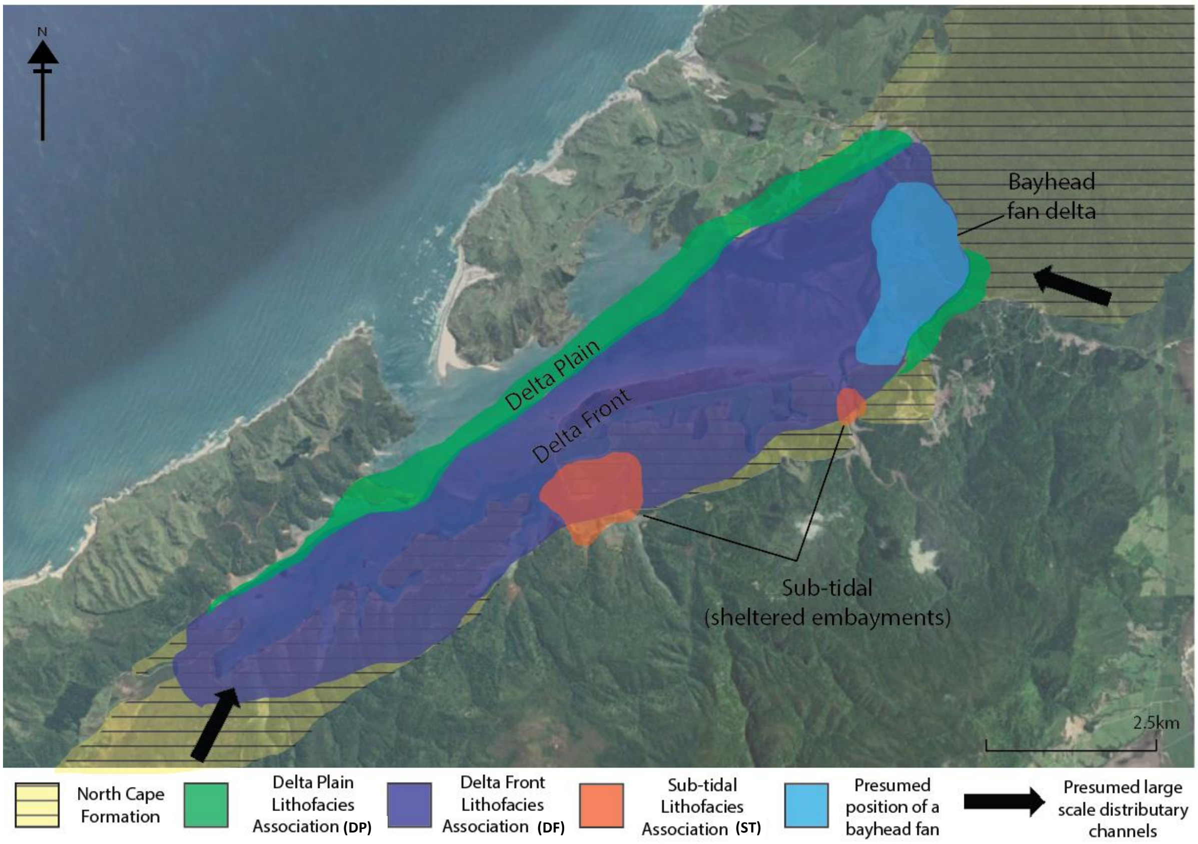


Figure 3.2 – Schematic representation of the interpreted paleodepositional environments present during the deposition of the North Cape Formation.

area is not known but can be compared with modern and ancient analogues to better understand lithofacies relationships and the transitions between the lithofacies associations that comprise it.

The North Cape Formation was deposited in a sandy, tide-dominated estuarine environment with little evidence for a local barrier. It likely had a high-sediment supply and was characterised by a dominant, coarse-grained distributary system in the northern area of outcrop. The lateral transitions from fluvial to tidally dominated deposition and their respective lithofacies are similar to the vertical facies model for the Cobequid Bay – Salmon River Estuary (Bay of Fundy) developed for macrotidal estuarine settings in Dalrymple et al. (1990). The model consists of bar-channel deposits with nested trough and planar sandstone beds; upper flow regime sand flats capped by mud flats and salt marsh sediments. Although this environment has a considerably larger tidal range than is inferred for the North Cape this model can be applied fairly generally and is considered a good analogue for the study area with the lateral variation observed in the transition from Lithofacies Association DF to ST described in this study.

New Zealand's Ohiwa Harbour in the Bay of Plenty, is a 24km² estuarine lagoon enclosed on either side by barrier spits. The majority of the harbour consists of tidal flats (70% by area.) and supports s rich shelly benthos diversified by mangroves and backed by local salt marshes (Richmond et al., 1984). The upper harbour sediments are poorly sorted, medium to fine sands, with coarse deposits restricted to channel and limited beach environments and finer material in the tidal flats, creeks and channel bank areas. The lower harbour is well sorted, with barrier beach, dunes, shoals and channel environments. Tidal currents dominate the sediment dispersal in the harbour, though small amplitude wind-forced waves are important in the movement of sediment in the tidal flats. The western barrier has accreted laterally over the last 2000 years, while the eastward barrier has experienced considerable erosion accelerating the infilling of the harbour. In general the sediments at the head of the estuary are poorly sorted and dominated by finer grained sediments reflecting minimal tidal currents, with minor wave reworking. The strongest tidal currents in the lower harbour have produced very well sorted, rippled and mega-rippled barrier beach, dune and entrance channel deposits. The deposits reflect an overall up harbour decrease in tidal flow energy (Richmond et al., 1984).

Most modern tide-dominated environments are generally hypersynchronous, which means that tidal range increases landward due to a funnel-shaped geometry of the drowned valley. As a result there are two areas of minimal tidal currents, the fluvial dominated deposition at head and the wave dominated deposition at the mouth of the estuary, separated by an area with stronger tidal currents in the middle of the estuary. The separation of this tidal energy produces similar deposits in two very different locations in the fluvio-marine transition (Dalrymple and Choi, 2007). It is therefore likely that the incidence of Delta Plain Lithofacies Association DP in the northeastern study area represent the head of the estuary, where minimal tidal energy reduces the overprinting observed in the Delta Front Lithofacies Association (DF).

The area of maximum tidal influence as a result of this hypersynchronousity can be seen in the Gironde Estuary, southwest France, where due to a lack of a barrier tidal processes are able to completely redistribute fluvially derived sediments that enter the estuary into elongate tidal bars (Aschoff et al., 2016). The local bayhead delta has been reworked into tidal bars by significant tidal energy, a process which may drive the deposition of the lithofacies that comprise Lithofacies Association DF of the delta front environment, particularly with increased distance from the head of the estuary.

An important ancient tide-dominated estuary to use for comparison is the Chimney Rock Tongue, Upper Cretaceous–Campanian in the Western Interior basin, Utah, USA. Plink-Björklund (2008) describes in high detail the distinct stratigraphic intervals that comprise the formation which switch from wave-dominated delta deposits to mixed-energy estuary deposits of an incised valley fill. Finally, the environment switches to a final transgression-regression sequence of a tide-dominated estuary. The succession contains tide influenced fluvial deposits; inner estuary tidal fills and local marsh deposits and; outer estuary upper-flow-regime tidal flat and sand bar deposits. These transgressive-regressive units were based on tidal ravinement surfaces that indicated flooding and subsequent *in situ* infilling of distributary river mouths. The shift from mixed-energy to tide dominant deposition with no wave-generated deposits is interpreted to be entirely the result of the position of the shoreline with relative increases in tidal energy to remove wave-built barriers. The geometry of such estuaries are open-mouth, devoid of the protection of sandy barriers.

These modern and ancient analogues help in understanding the likely geometry of the North Cape Formation during its deposition in the study area. An open-mouth estuary is the likely form for the estuary during the deposition of the North Cape Formation in the study area. The well-established, vegetated dune and barrier beach lithofacies related to barrier spits in the Ohiwa Harbour are not described in the outcrops presented in this study, thus it is interpreted that during deposition there was not a significant local wave barrier. The interpretation of a lack of any barrier can only be applied to the outcrop scale as the wave dominated depositional region of the estuarine system may occur in the offshore portion of the Pakawau Sub-basin. There is no seismic nor drill data for this area due to close proximity to land and no previous interest in the characterisation of estuary end-member type. The funnel-shaped geometry of the estuary seems to have focused tidal energy observed in the Delta Front Lithofacies Association (DF) during North Cape deposition. The area headward of this deposition does not experience tidal reworking and is dominated by fluvial processes, represented by the Delta Plain Lithofacies Association (DP). As is observed in the Gironde Estuary it is expected that fluvial deposition in the North Cape Formation has been reworked by a local bayhead delta in the northeast, resulting in the lithofacies that comprise the Delta Front Lithofacies Association (DF). The cyclic transgressive-regressive units observed in the Chimney Rock Tongue setting are similar to those described within the Sub-tidal Lithofacies Association (ST) in the central region of the study area.

3.5 – Conclusions

The assessment of mixed fluvio-tidal estuarine settings in both ancient and modern settings suggest that the North Cape Formation was deposited in a sandy, tide-dominated estuary which contained a local bayhead fan delta in the northeast, smaller scale tidal distributary channels throughout and at least some partially sheltered tidal embayments. The tidal dominance, sand dominated deposits, as well as the lack of wave-generated deposition supports the paleogeographic reconstruction for the study area not having a sand barrier at the estuary mouth. Additionally, cyclic alternations between sub-tidal and supra-tidal deposition noticeable within the Sub-tidal Lithofacies Association A3 may reflect localised transgressive and regressive sequences. These could be in response to sea-level fluctuations and from local or regional subsidence.

Chapter 4 – Petroleum Potential

4.1 – Introduction

Cretaceous petroleum plays are becoming increasingly important in the consideration of alternative targets in the Taranaki Basin. Existing petroleum production is to date only from Paleocene-Pliocene successions, although the coals and coaly successions of the Late Cretaceous represent the main hydrocarbon source for these younger productive units (King and Thrasher, 1996; Higgs et al., 2007; Uruski, 2008; Higgs et al., 2010). Limited offshore well penetrations have identified potential Late Cretaceous sandstone reservoirs in the Rakopi and North Cape Formations in both non-marine, highly quartzose conglomerates, sandstones and coals, and shallow-marine sediments (Robinson and King, 1988; Collen and Newman, 1991; Bal and Lewis, 1994; Browne et al., 2008).

The North Cape Formation is known to include some good-quality potential reservoir sandstones , particularly in the likely widespread transgressive shelf sands in the Deepwater Taranaki Basin (Uruski, 2008). 17 wells have penetrated the Late Cretaceous North Cape Formation, with a number drilling TD to basement or mid-Cretaceous strata. Thick Cretaceous successions are penetrated by the Cook-1 and Cape Farewell-1 (onshore) wells within the Pakawau Basin. Core-analyses from these wells is sparse, though do demonstrate good reservoir quality in the Tahi, Tane and Pukeko areas each reporting samples in excess of 100mD (Higgs et al., 2010). No obvious porosity to permeability trend can be established across all wells, although the authors show that most samples with >0.1mD all exceed 10% in measured porosity.

A better understanding of the geometry and petrophysical properties of tide-dominated deposits is becoming increasingly important, particularly with the large number of important hydrocarbon occurrences hosted in tidal deposits (e.g. the McMurray Formation oil sands, Alberta, Canada) (Dalrymple and Choi, 2007). Additionally bayhead delta environments tend to sequester sandy deposits that can form excellent hydrocarbon reservoirs (Aschoff et al., 2016). So characterisation of the petrophysical properties of the different depositional sub-environments present within the North Cape Formation was considered an important component of this thesis.

Although many studies reiterate the petroleum potential of Late Cretaceous successions (Robinson and King, 1988; Bal, 1992; King and Thrasher, 1996; Higgs et al., 2010) the assessment of petrophysical properties at outcrop scale has been neglected for NW Nelson formations. This study presents both *in situ* and lab analyses to provide insight into individual lithofacies, the results of which could be extrapolated to the deeper marine North Cape Formation successions further north.

4.2 – Petroleum systems of the Taranaki Basin

The Taranaki Basin represents the only commercially-producing hydrocarbon region in New Zealand, with all major petroleum systems involving Neogene-aged structural traps related to the development of the Australia-Pacific plate boundary. The primary source rocks within at least the southern and central Taranaki Basin are identified as coals within the Late Cretaceous Pakawau and deeper Eocene Kapuni Group sediments (Collen and Newman, 1991; King and Thrasher, 1996; Cook and Gregg, 1997). Generation and migration of the hydrocarbons present within the Taranaki Basin is modelled to have occurred fairly late in the basin's history. It is likely that hydrocarbon generation and expulsion may have occurred earlier within Late Cretaceous-Eocene expressions under high heat flow, though many are assumed lost to the basin, or have potentially remigrated into younger reservoir successions during the Neogene structural inversion (Cook and Gregg, 1997).

Potential and proven reservoirs are within Late Cretaceous-Eocene terrestrial, paralic and near shore sandstones with younger reservoirs more varied, including fractured Oligocene limestones, Miocene volcaniclastics and turbidites, and Pliocene deep-water sandstones (Figure 4.1) (New Zealand Petroleum & Minerals, 2015). The coal-bearing Late Cretaceous Rakopi Formations is a proven source and has been more recently suggested as a potential reservoir (King and Thrasher, 1996; Higgs et al., 2010) and it is likely the channel sandstones and higher energy shoreface sandstones of the North Cape Formation may also represent suitable reservoir rock, while local disseminated coals and organic rich units may provide a more unconventional petroleum play (King and Thrasher, 1996; Higgs et al., 2010). Siliciclastic reservoirs in Late Cretaceous successions in the Taranaki Basin report porosities between 15-25%, while permeabilities average 50-100mD (Cook and Gregg, 1997).

Rotary core or sidewall core samples from the North Cape Formation on the western platform (at Pukeko-1) demonstrate the presence of good quality reservoir sandstones at depths in excess of 4km with permeability (kH) measurements up to 300mD. Additionally, the marine Island Sandstone Member of the North Cape Formation, encountered in the Tane-1 well, at ~3500m still exhibits excellent primary porosity and permeability characteristics. Figures in excess of 25% porosity and 800mD (millidarcies) permeability have been recorded in the well (Shell BP and Todd Exploration Services, 1976). Relict porosity is present in most of Pakawau Group sandstones, although is usually modified by diagenesis (King and Thrasher, 1996).

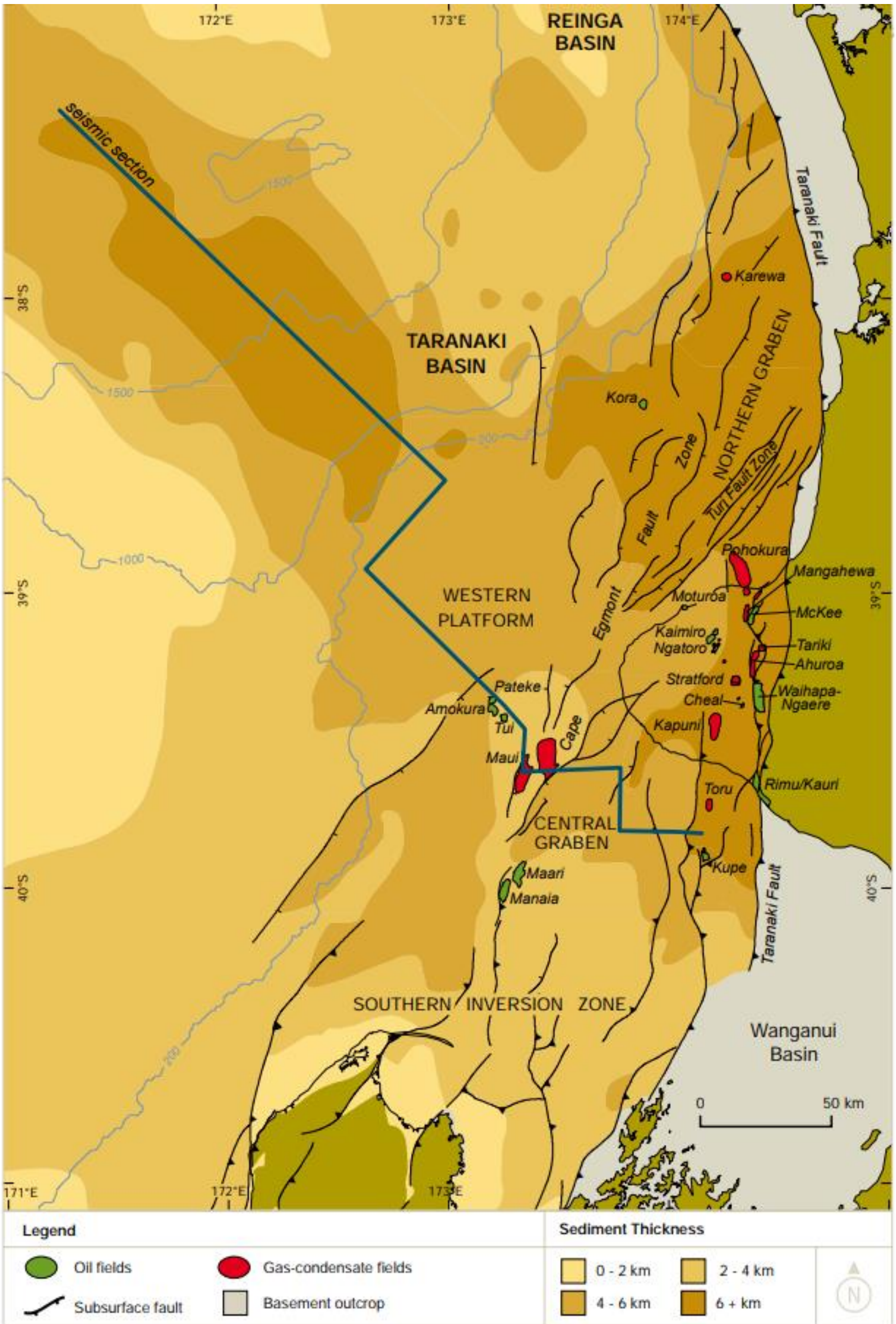


Figure 4.1 - Oil and gas-condensate fields and structural elements of the Taranaki Basin, (New Zealand Petroleum & Minerals, 2015).

The best prospects for hydrocarbon source and reservoir units at the Cretaceous level in the Taranaki Basin lie at the base of the Paleocene succession, however the depth of burial necessary for thermal maturation for hydrocarbon generation (>5km) means that some amount of primary porosity is likely lost (Collen, 1988; Collen and Newman, 1991). Secondary porosity is therefore crucial for commercial hydrocarbons to accumulate at depth and to facilitate migration to suitable reservoirs higher in the successions. According to Collen (1988) most porosity and permeability within New Zealand's commercial hydrocarbon fields is of secondary origin, likely produced by the dissolution of liable grains.

4.2 Methods

In order to assess the reservoir potential of the North Cape Formation, relative petrophysical properties of available outcrop were measured both *in situ* during field work and by a variety of laboratory techniques. This study examines the petrophysical characteristics of the lithofacies in the North Cape Formation identified in Chapter 2.

4.2.1 – In-situ measurement:

Gamma Profiles:

Spectral U, Th and K gamma ray (GR) values and total count data (all 3 elements combined) were acquired using the handheld Gamma Surveyor II scintillometer tool (GF Instruments) (http://www.gfinstruments.cz/version_cz/index.php?menu=gi&cont=surveyor_II_ov). Gamma ray values were collected to produce a vertical profile through representative sections after preliminary stratigraphic sections were produced. Draft stratigraphic sections provided clear lithological markers and ensured measurement points could be correctly assigned to their respective lithofacies.

Measurements were collected over a five-day period in order to ensure the most similar atmospheric conditions, with readings collected at 60cm intervals or where a lithology change was first observed Ambient readings were recorded prior to outcrop measurement in case later adjustments needed to be made. At individual sites measuring time was restricted to 120 seconds to ensure the most extensive coverage of measured sections, with lithology described at every point to more accurately tie readings to the described sections. Measurements produced K, U, Th and total count data which was transferred into Microsoft Excel and plotted alongside the corresponding stratigraphy.

Permeability:

In situ measurement of horizontal permeability (kH) was undertaken for rock outcrop using a hand held NER Tiny-Perm permeameter device (http://www.ner.com/site/systems/item/27-

tinyperm.html). Suitable outcrop was selected, where surfaces were dry and clear of any matter that may interfere with measurement (e.g. sea weed, lichen etc.), additionally, highly weathered surfaces were avoided or knocked away with a hammer. Care was taken to avoid highly cemented surface units as these may produce an inaccurate representation of the conditions offshore. *In situ* measurements were made on the surface of representative lithofacies with repeat measurements collected in order to establish reliability. Measurements were collected over 160 seconds, or until equilibrium was met. A number of outcrops were not easily accessible at the time of measurement, thus resulting in fewer measurements than intended. Additionally, despite control measurements there was considerable range in readings at the same site and within control measurements. Obvious outliers, infinity readings and errors in measurements were excluded from analysis.

4.2.2 – Laboratory Analyses

Porosity

Thin section analysis (Visual Porosity):

Porosity was assessed through visual quantification of void space versus grain using point count analyses. This was carried out on 36 thin sections produced from hand samples representative of a range of grain sizes within lithofacies of the outcropping North Cape Formation. It should be noted that analysis of porosity was not collected for the coal lithofacies **(C and CZ)** as it was too difficult to view grain size under the microscope in addition, difficulties in preparing thin sections of conglomerate **(G)** lithofacies meant that this was not included in such visual porosity measurements

Thin sections were prepared using standard laboratory techniques and stained with blue die to identify void space. Slide advancements were set to 1mm and 0.5mm depending on grain size, and thin sections were periodically moved until a 200 point count was reached. At each advancement it was noted whether the cross hairs intersected void space or grain and the subsequent proportion of each was reported as a percentage.

$$\Phi v = \left(\frac{grain - void}{total\ count}\right) \times 100$$

Values are reported here as Φv (visual porosity). Mud matrices, diagenetic features and precipitates were considered grain space as they would not allow fluid flow.

Core analysis (Core Measured Porosity):

Drill core was extracted from appropriate outcrop for porosity measurements using the AccuPyc II 1340 Pycnometer (http://www.micromeritics.com/Product-Showcase/AccuPyc-II-1340.aspx).

20 millimetre diameter drill core was prepared to ensure consistent surfaces for length and width measurements. These measurements were repeated 3 times and averaged to establish sample volume. Samples were dried at 60°C for 48 hours to remove any moisture and clear void space. The pycnometer readings return a sample grain volume in addition to a standard deviation which was used alongside sample volume measurements to establish the proportion of pore spaces in the samples, expressed as a percentage (Table 4.2).

$$\Phi c = \left(\frac{volume\ (m^3) - grain\ volume\ (m^3)}{volume\ (m^3)}\right) \times 100$$

Values are reported here as percentages and described as Φc (porosity measured form core) with the relative orientations of extracted core noted.

Permeability:

Permeability was also assessed on the available core samples using the Bronkhurst EL-FLOW Prestige Mass Flow Meter (MFM) technology. Flow volumetric gas flow rate (mL/min) and differential pressure (millibar) readings were taken at four intervals for each core sample to establish a trend. This data was directly input into an Excel spreadsheet supplied by _ which reported linear slopes and intercepts that corresponded to raw permeability vales (k). Where necessary a Forchheimer correction was applied to the data to establish an alternative permeability (k) for each sample. Permeability (k) was initially reported in m^2 and subsequently converted to millidarcies (mD) to allow direct comparison to *in-situ* and well log permeabilities (Table 4.3). The nature of applied load to the core samples resulted in damage to cores, therefore permeability measurement on the Oyster Point core samples measured for porosity (Φc) could not be completed. Core permeability is reported here as kc, in millidarcies (mD) and the drilling direction was indicated to establish whether measurements reflect horizontal or vertical permeability.

4.3 – Results

4.3.1 Porosity:

Core porosity (Φc)

Porosity measurements on core samples (Φc) (Figure 4.2 , Table 4.1) show distinct patterns based on geographic locality and depositional setting, with porosity considerably lower in the Oyster Point outcrop of the study area. Additionally the lithofacies core sampled from this locality also report lower porosity (Φc) than the core samples taken in equivalent lithofacies at other outcrops. Porosity measurements range between 17- 21% at Oyster Point while porosity values range between 30-36%

at Pecks Point and Pecks Point Cgl outcrops and the largest spread occurs within the Wairoa River North locality with porosity ranging between 23-37%.

Finer grained lithofacies tend to exhibit lower porosity where the intergranular space is reduced although there are some anomalies in this trend. A porosity of with 37% was recorded for a fine sandstone heterolithic lithofacies (Hl) core taken at Wairoa River North outcrop.

Overall the Oyster Point samples record lower core porosity, it is likely this is a product of the better levels of sorting in the lithofacies that characterise the Delta Plain Lithofacies Association (A1) present in the western outcrops. Additionally there is a considerable increase in iron nodules and iron precipitates that may reflect products of diagenesis that could have reduced intergranular porosity for these samples

Visual porosity (Φv)

Visual porosity Φv was analysed for 36 thin sections, representing a range of lithofacies, grain sizes and outcrop locations. Samples showed a more obvious spread in porosity values across the different lithofacies, where finer grained lithofacies recorded lower overall Φv values. Visual porosity ranged from 6.3 to 46% in samples with grain size from coarse silt in the bioturbated carbonaceous siltstone **(Zb)** to conglomerate lithofacies **(G)** with a coarse sandstone matrix.

The lowest recorded Φv values were from very fine to fine grained interbedded heterolithic sandstone **(Hl)** and carbonaceous sandstone **(CS)** at the Oyster Point locality. This is attributed to finer grain sizes and increased cementation and iron fluidisation when compared with equivalent lithofacies at other outcrops. Wavy and cross-bedded sandstones **(Sw, Sxt)** record the greatest porosity values which are interpreted to be due to their increased grain sizes and subsequent intergranular space and overall well to moderate sorting.

There are some unexpectedly high porosity results for the heterolithic **(Hl)** and planar laminated **(Sp)** sandstones collected in eastern outcrops. This is likely related to the interbedded nature of these units, in addition to the generally good levels of sorting particularly in the upper plane beds of these lithofacies in these regions of the study area.

There is a marked difference in recorded porosity ranges between visual and core porosity values which is expected to be related to the difference between qualitative and quantitative analyses. Overall Φv values are lower than the Φc values. Core porosity (Φc) values are considered the more reliable as they are measured over a greater surface area and represent porosity in 3D space, while the Φv values record porosity along a flat surface so may underestimate, or in some cases overestimate the relative petroleum potential of the measured lithofacies.

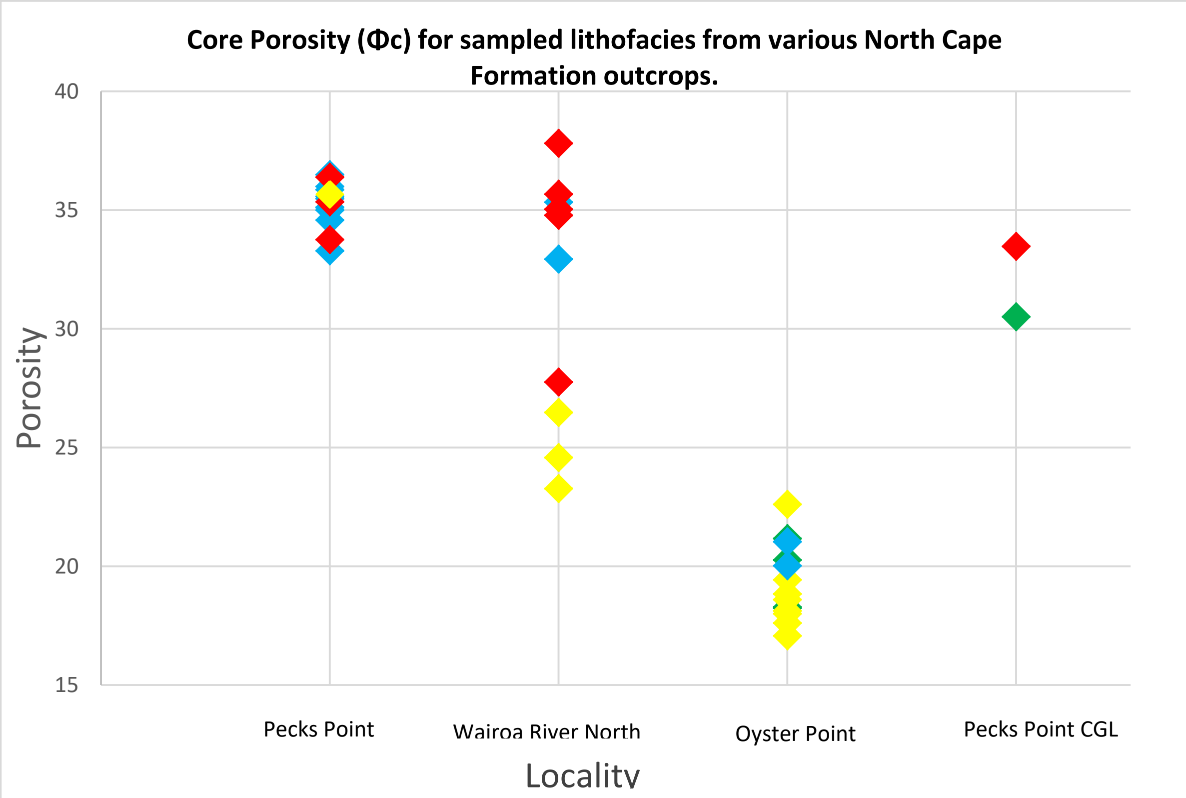


Figure 4.2 - Core porosity (Φc) for core samples collected at select outcrop localities. Symbols and the corresponding lithofacies are included in Table 4.1.

Symbol	Lithofacies	Porosity (Φc)		
		Range (%)	Average (%)	Count (n)
◆ (green)	CS	18.2 - 30.51	21.70	4
◆ (yellow)	Hl	7 - 29.4	16.4	8
◆ (red)	Sw	23 - 38.5	30.3	8
◆ (blue)	Sxt	13 - 46	27.6	10

Table 4.1 – Summary of measured core porosity (Φc) for various lithofacies. Data in the table is plotted in figure _.

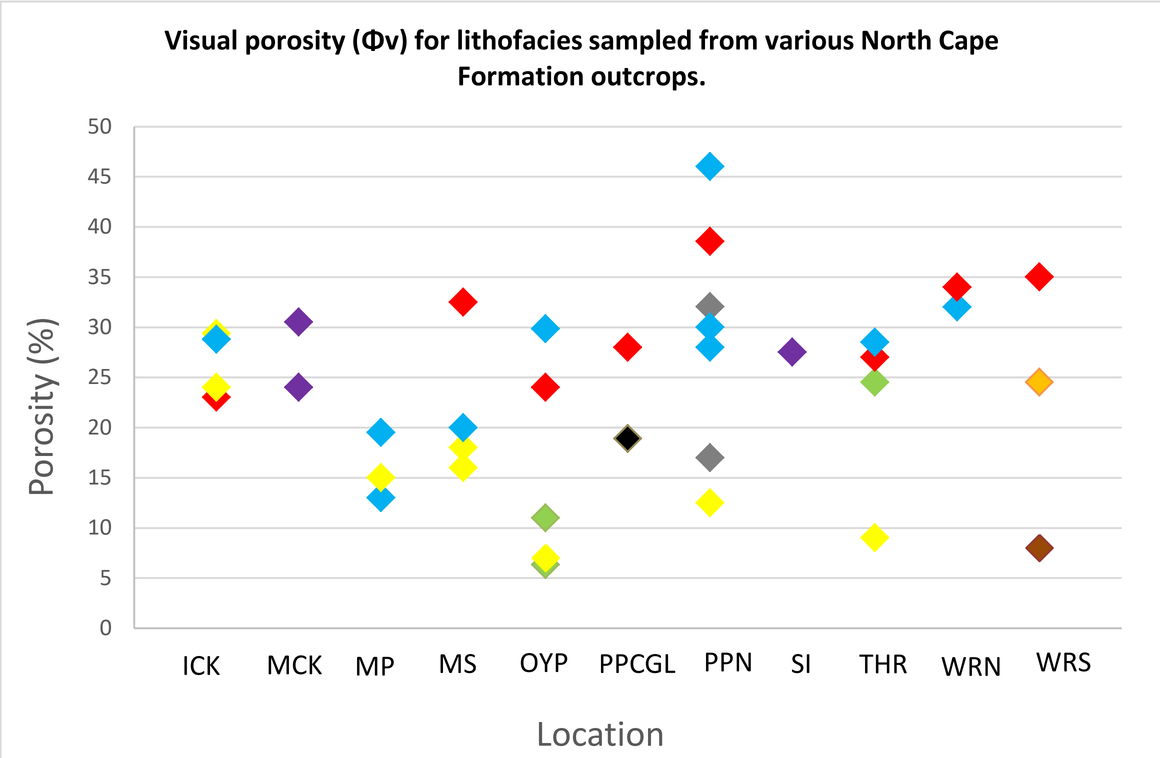


Figure 4.3 – Visual porosity (Φv) for thin section samples collected at various North Cape Formation outcrop localities. Symbols and the corresponding lithofacies are included in Table 4.2. Location codes: ICK , Island Creek; MCK, Muddy Creek; MP, Maori Point; MS, Mangarakau Swamp; OYP, Oyster Point; PPCGL, Pecks Point Conglomerate; PPN, Pecks Point; SI, Southern Inlet; THR, Te Hapu Road; WRN, Wairoa River North; WRS, Wairoa River South.

Symbol	Lithofacies	Porosity (Φv)		
		Range (%)	Average (%)	Count (n)
	Zb	8	8.0	1
	CS	6 - 24.5	18.1	2
	DHI	24.5	24.5	1
	Hl	7 - 29.4	16.4	8
	Sp	24 - 30.5	27.3	3
	Sw	23 - 38.5	30.3	8
	Sxt	13 - 46	27.6	10
	Sxp	17 - 32	24.5	2
	G	18.9	18.9	1

Table 4.2 – Summary of visual porosity (Φv) values for the sampled lithofacies. Data is presented graphically in Figure 4.3.

4.3.2 – Permeability

Core analysis:

Permeability measurements on available core samples show that there are considerable differences between the sampled lithofacies, particularly in relation to their sample location and lithofacies association. Overall, samples collected at Pecks Point and Pecks Point CGL localities show the highest core permeability measurements across the four sampled lithofacies. Permeability ranges from 19 to 545mD across the cores (Table _) with the highest values recorded in the trough crossbedded sandstone **(Sxt)** lithofacies. The Wairoa River samples show a considerable range in permeability values, ranging from 0.33 to 538mD. The lowest permeability values were associated with the very fine grained heterolithic sandstone **(Hl)** lithofacies despite moderate core porosity values (Figure 4.4). This is interpreted to be a product of the interbedded very fine grained and siltstone that comprise the lithofacies. The larger grain sizes in the medium to coarse trough crossbedded **(Sxt)** and wavy bedded **(Sw)** sandstones explain the relatively high permeability measurements across the sampled cores. Although only one sample was measured the carbonaceous sandstone **(CS)** lithofacies it shows good permeability at the Pecks Point CGL locality which is likely related to the good overall levels of sorting.

As a result of damage to available cores permeability measurements were not able to be collected for the Oyster Point samples.

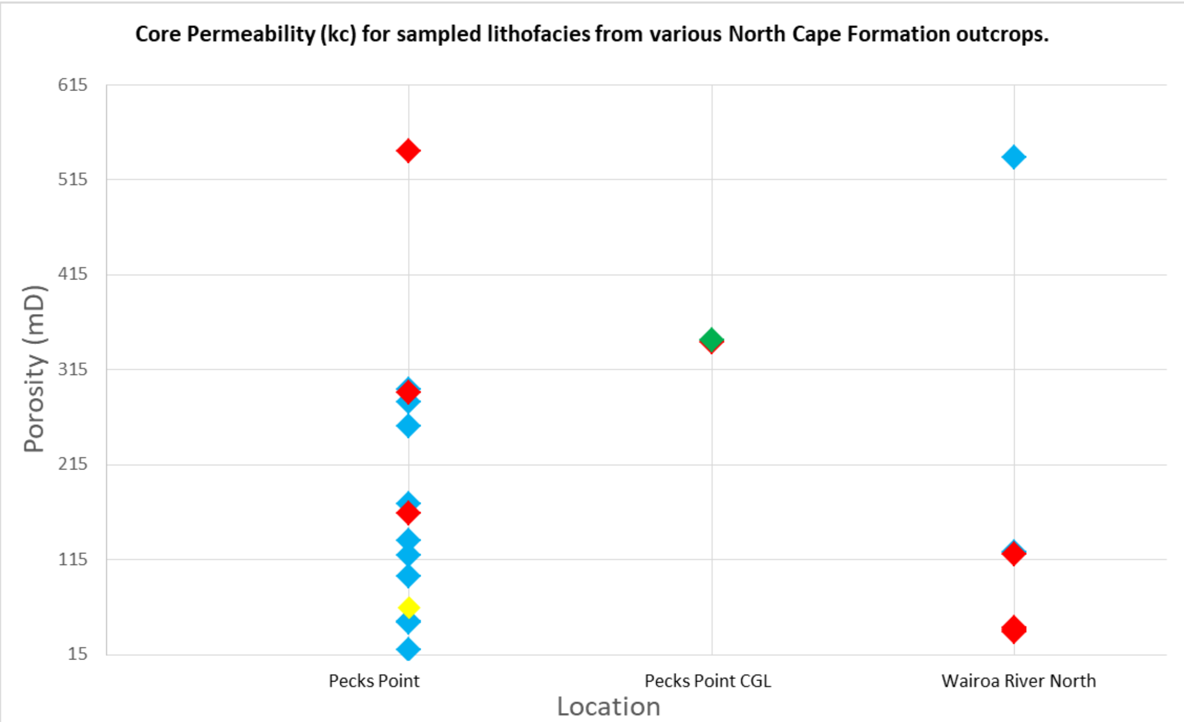


Figure 4.4 – Core permeability (kc) for core samples collected at various North Cape Formation outcrop localities. Symbols correspond to the lithofacies included in summary Table 4.3.

Symbol	Lithofacies	Permeability (kc)		
		Range (mD)	Average (mD)	Count (n)
◆	CS	345.70	345.70	1
◆	Hl	0.33 - 64.54	16.66	4
◆	Sw	14.67 - 545.05	172.13	9
◆	Sxt	19.93 - 538.68	173.72	10

Table 4.3 – Summary of the core permeability (kc) values for the sampled North Cape Formation core. Data is presented graphically in figure 4.4.

***In situ* analysis:**

Horizontal permeability was measured directly on the outcrop face using a hand-held permeameter (as described above). Measurements were undertaken of all lithofacies that comprise the North Cape Formation in the study area aside from the coal dominated lithofacies. Measurements showed significant variability and potential inconsistencies in the values recorded by the device, and these need to be considered when interpreting results.

Overall, permeabilities for measured outcrop range between 0.02 millidarcies (mD) in bioturbated carbonaceous siltstone **(Zb)** lithofacies and 930mD in the conglomerate **(G)** lithofacies with a very-coarse sandstone matrix. The low porosity in the **Zb** lithofacies is due to both the fine grain size and the effects of bioturbation both contributing to a reduced permeability. Permeability values in the finer grained sandstones of the carbonaceous sandstone **(CS),** heterolithic sandstone **(Hl)** and planar laminated sandstone **(Sp)** lithofacies are moderate, averaging 39mD (n=9), 36mD (n=96) and 21mD (n=41), respectively. The increased permeability is interpreted to be related to larger grain size and overall better levels of sorting.

Wavy bedded **(Sw)** and trough **(Sxt)** and planar **(Sxp)** cross bedded sandstone lithofacies record relatively high average permeabilities, 143mD (n=38), 227mD (n=51) and 129mD (n=6), respectively. Conglomerate **(G)** lithofacies measured the highest *in situ* permeability, averaging 417mD (n=11).

Table 4.4 – Summary of the *in situ* permeability measurements taken on various lithofacies in the field area

Lithofacies	Permeability (*in situ) (mD)*		
	Range	**Average**	**Count (n)**
CS	0.08 - 92.83	39.49	9
Zb	0.02 - 14.7	4.29	13
Hl	0.06 - 364.1	36.87	96
Sp	0.05 - 183.1	20.77	41
Sw	3.47 - 898.5	143.82	38
Sxt	2.98 - 932.5	227.114	51
Sxp	9.21 - 496.7	129.13	6
G	115.1 - 930	417.47	11

4.3.3 – Gamma Ray

Gamma Ray (GR) profiles collected with a hand-held Scintillometer show relatively uniform GR values through vertical outcrop sections, with occasional high values recorded at intervals of interbedded siltstone and fine grained sandstone units, mud drapes within coarse grained lithofacies and the few coal units (Section 4.3.3.1). Overall the gamma profiles maintain a fairly consistent and uniform vertical trend through the measured sections.

In the GR profiles recorded in the Cook-1, Cape Farewell-1 and Fresne-1 wells the North Cape Formation is characterised by a steady GR log profile, when compared with the underlying Rakopi Formation and overlying Farewell Formation. There is an abrupt transition from the serrate GR log profile of the coal bearing Rakopi Formation to the uniform log pattern of the North Cape Formation and an additional abrupt change to the overlying quartz rich Farewell Formation (Suggate, 1956; Roncaglia et al., 2013). The North Cape Formation in the Cook-1 well shows a relatively uniform GR log profiles with a few intervals of higher GR values associated with coal beds and interbedded siltstone and sandstone units. There GR logs for both the Fresne-1 and Cape Farewell-1 wells are more irregular (fluctuating values), with the North Cape Formation, with deviations associated with gravelly glauconitic sandstones and conglomerate.

To summarise, the above observations can be taken to indicate that the North Cape Formation has a more uniform gamma profile than the underlying Rakopi Formation. This reflects a higher net:gross ratio, where the North Cape Formation has a higher proportion of sandstone relative to the Rakopi Formation and relatively thin interbedded fine-grained beds (siltstones and coals) compared to the Rakopi Formation. The typically irregular gamma curve in wells that intersect the Rakopi Formation is taken to indicate that the finer-grained interbeds are thicker than those intervals in the North Cape Formation. The more varied gamma profiles through the North Cape Formation in the wells to the north (Fresne-1 and Cape Farewell-1), is likely an indication that the lithofacies are more varied in basinwards direction (more marine interbeds) with a lower net:gross (sand content) than the units in the field area.

4.3.3.1 – Gamma Ray (GR) Profiles

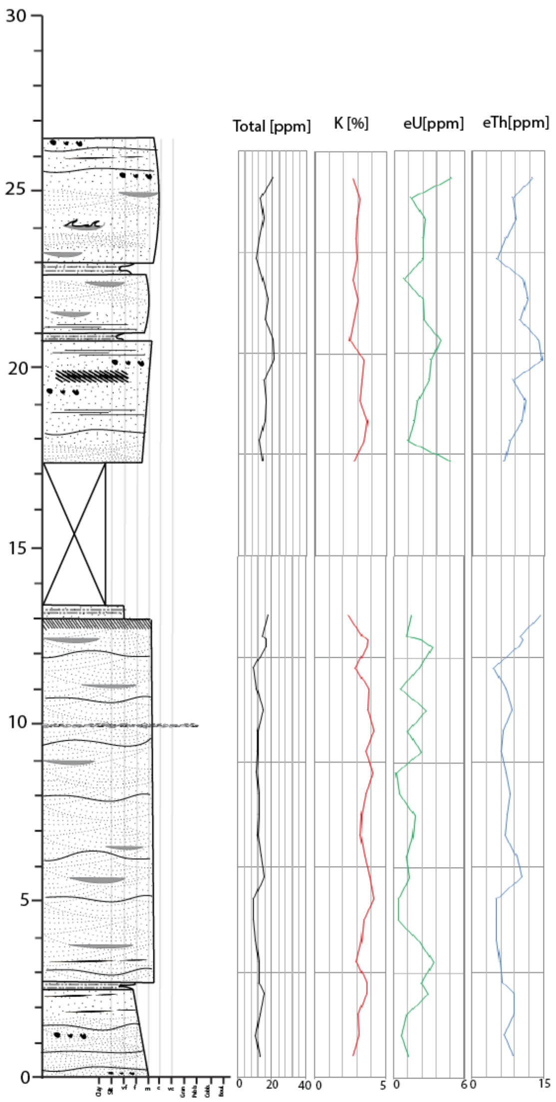
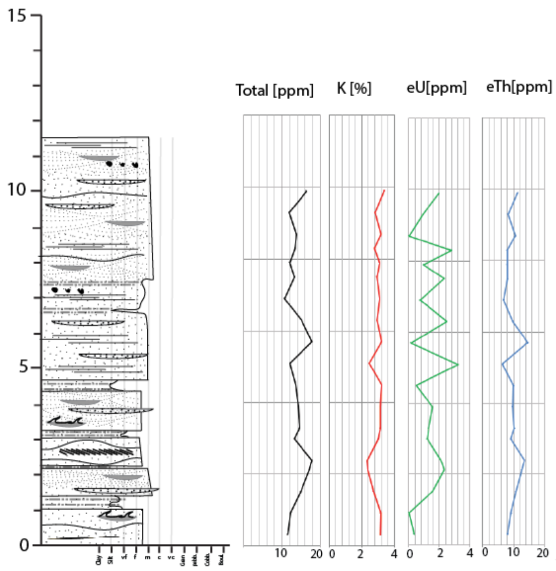


Figure 4.5 – Gamma Ray (GR) profile measured for the Island Creek sections. Incomplete GR profile occurred as a result of inability to access the very top and bottom of the outcrop, in addition to obscured outcrop for measurement.



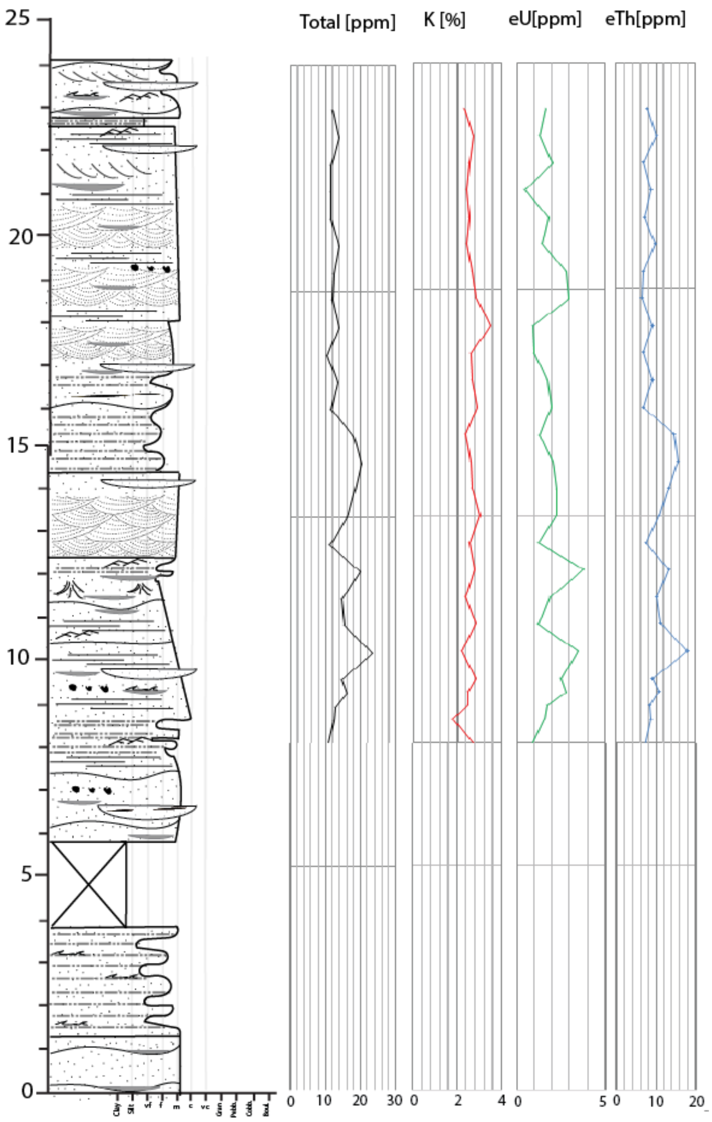


Figure 4.6 – Gamma Ray (GR) profile measured for the Muddy Creek section. Incomplete GR profile occurred as a result of inability to access the very top and bottom of the outcrop for measurement.

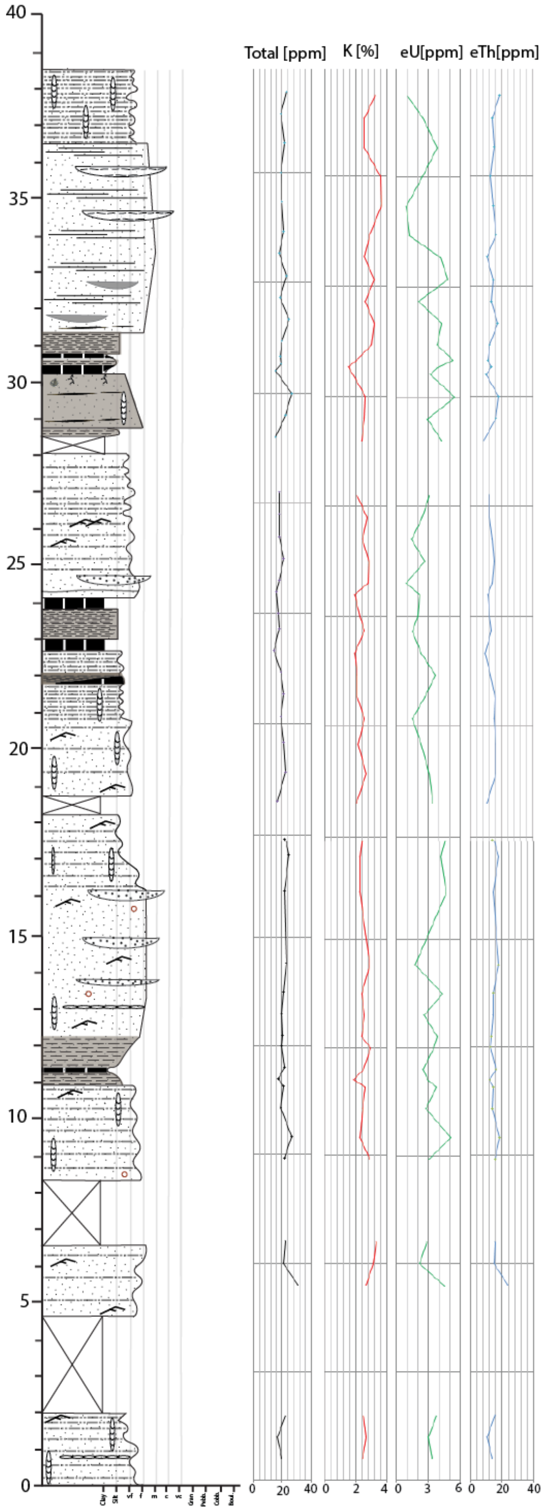
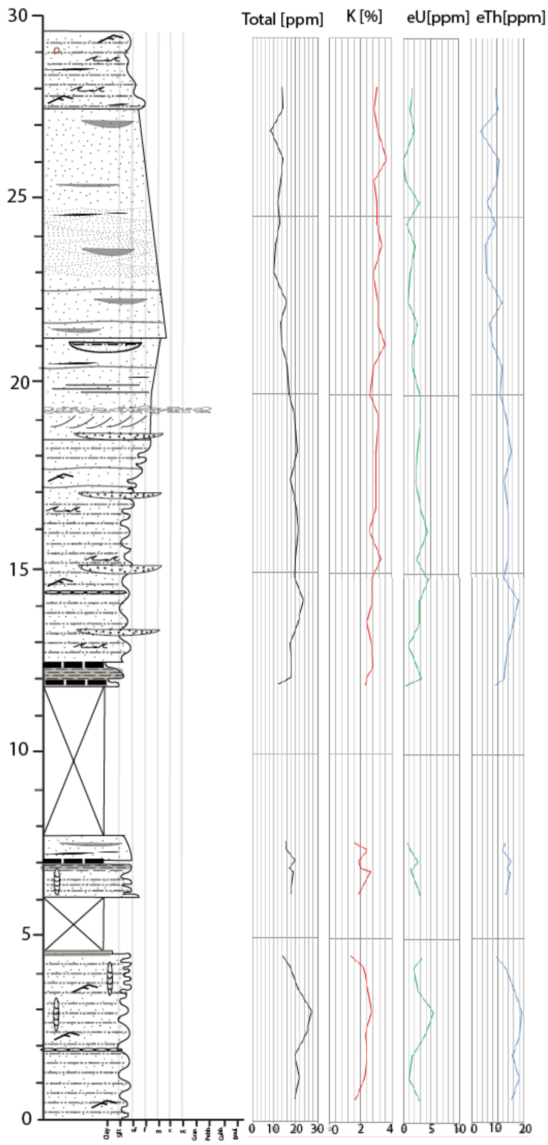


Figure 4.7 – Gamma Ray (GR) profile measured for the Wairoa River South (A) and Wairoa River North (B) sections. Incomplete GR profile occurred as a result of inability to access the very top and bottom of the outcrop, in addition to obscured outcrop for measurement.



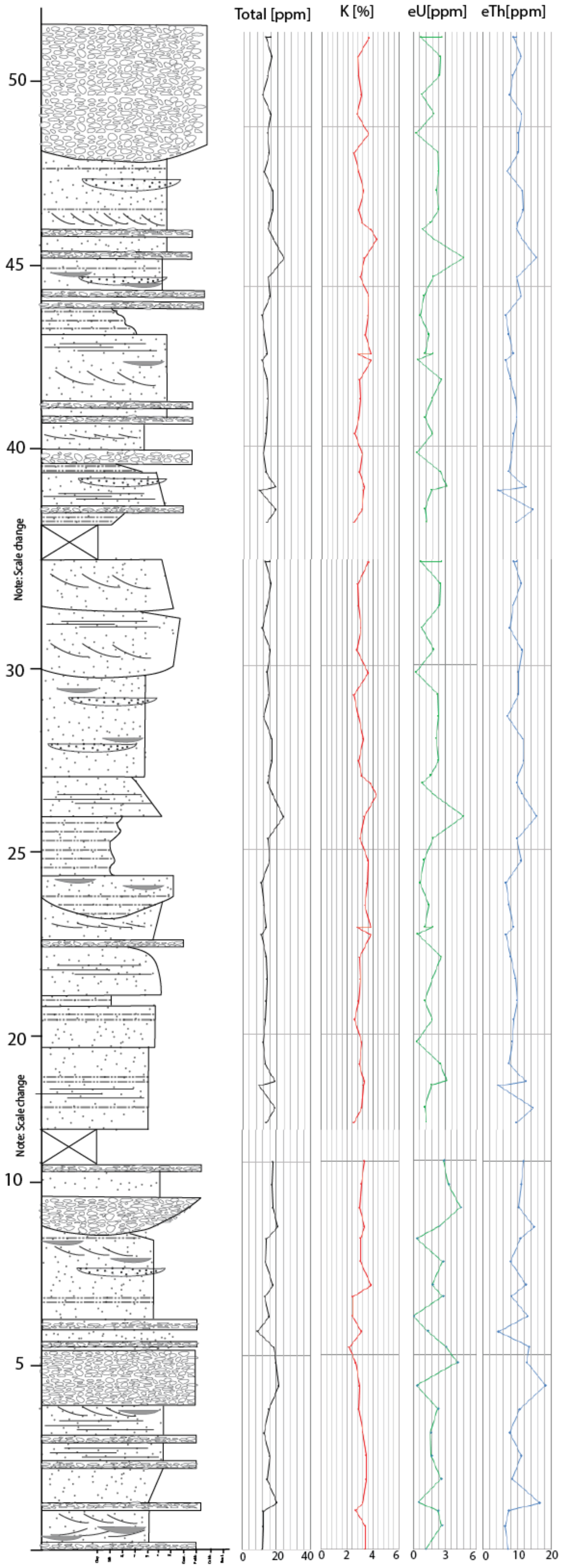


Figure 4.8 – Gamma Ray (GR) profile measured for the Pecks Point CGL section. Breaks in readings are associated with obscured outcrop for measurement

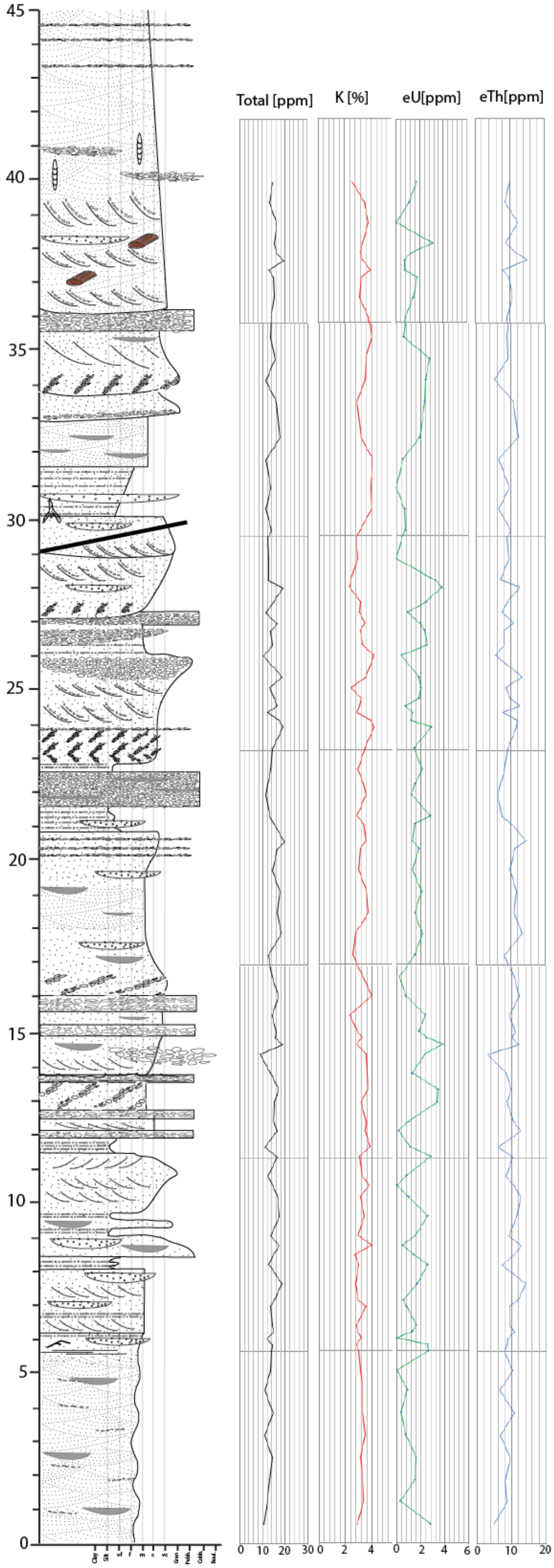


Figure 4.9 – Gamma Ray (GR) profile measured for the Pecks Point North section. Incomplete GR profile occurred as a result of inability to access the very top and bottom of the outcrop for measurement.

4.4 – Discussion

Late Cretaceous reservoir facies within the Taranaki Basin have been identified from both outcrop and limited subcrop data sources (Higgs et al., 2010). Reservoir facies in the North Cape Formation comprise a channel, shoreline and shallow marine sandstones. Based on more recent modifications to paleogeographic reconstructions (Strogen et al., 2011), it assumed the best developed reservoir facies of the North Cape Formation occur in more western regions of the Taranaki Basin.

In a general sense, it is commonly observed that the best reservoir quality lithofacies are those deposited in high-energy environments due to good sorting and low proportions of detrital clay (Peterson and Clarke, 1991). The best reservoir facies in the North Cape Formation are considered to be marginal marine channel and shallow marine shoreline sandstones (Higgs et al., 2010). This corresponds to the tidally influenced Delta Front Lithofacies Association (DF), and where present, the Delta Plain Lithofacies Association (DP) described in this study. Lithologies in those associations typically have porosity measurements in excess of 20% in the measured wavy and cross-bedded sandstones of both Lithofacies Association DP and DF. *In situ* permeability measurements in the crossbedded **(Sxp, Sxt)** and wavy sandstone **(Sw)** lithofacies are good, with average values between 130 and 417 millidarcies (mD). Although core permeabilities are lower than *in situ* permeability measurements both **Sxt** and **Sw** lithofacies show good reservoir potential with 172 and 173mD, respectively. The best quality reservoir units, with both good porosity and permeability reading were those of the coarser grained lithofacies in the northeastern region of the study area.

Interbedded heterolithic sandstones **(Hl)** and planar laminated sandstone **(Sp)** lithofacies may also prove good potential reservoirs. **Hl** lithofacies records core porosities in excess of 23% in both the Delta Front and Sub-tidal Lithofacies associations and moderate average permeability of 36mD along the eastern coast of the study area. **Sp** lithofacies, though not assessed in core, shows good visual porosity averaging 27% and moderate *in situ* permeability, averaging 21mD. Based on the Oyster Point cores porosity values the heterolithic lithofacies **(Hl)** has moderate porosity, ranging between 17-22% in the equivalent Delta Front Lithofacies in the western region. Lower recorded core and visual porosity in the western outcrops are interpreted to be the result of finer average grain size (fine sand). Additionally, the lithofacies described in the western outcrop show considerable iron fluidisation and abundant iron nodules that may represent greater effects of local cementation and diagenesis which are likely to have reduced porosity and limit fluid flow resulting in lower permeability readings. The least prospective reservoirs in the North Cape Formation are the carbonaceous **(CS)** and bioturbated carbonaceous siltstone **(Zb)** lithofacies, with the lowest recorded permeability and visual porosity. The finer grain size, as well as the effects of bioturbation and smearing of grains in the **CS** and **Zb** lithofacies limit both porosity and permeability.

Reservoir potential is more challenging to characterise for the conglomerate **(G)** lithofacies as samples for measurement were difficult to collect. It is expected that these units would record good porosity and permeability as a result of a coarser grain sizes and have intergranular macroporosity. However, localised mud drapes may reduce permeability and act as baffles to hydrocarbon flow, particularly in the tidally affected units (Aschoff et al., 2016). The local conglomerate lithofacies in the northeastern section recorded very high *in situ* permeability, ranging between 115-930mD and would be expected to show good porosity, thus likely represents a good reservoir. It is important to consider the relative reservoir potential of this lithofacies as conglomeratic units are prominent in the offshore Fresne-1 well (Roncaglia et al., 2013).

In addition to considerations of reservoir potential, the Pakawau Group has been identified as a source rock for hydrocarbon (Thompson, 1982; Higgs et al., 2010). The northern-most Pakawau Sub-basin has also been interpreted to provide the source kitchen for the active petroleum systems the northeast of the Pakawau Sub-basin. These Upper Cretaceous kitchens contain relatively thick coal measures made up of numerous coal seams interbedded with carbonaceous sandstones and siltstones deposited in lower coastal plain environments with fluvio-estuarine channels and swamps (figure 4.1) (Smith et al., 2014). Onshore expressions of the Late Cretaceous North Cape Formation within the study area support this interpretation, with numerous thin coal beds **(CZ, C)** throughout the outcrop commonly interbedded with highly carbonaceous sandstones and siltstones **(Zb, CS).**

Previous analyses of the Pakawau Coal Measures (a member of the North Cape Formation by some authors) report that good thermal maturity had been reached by the Late Miocene-present, with sharp increases in maturity with depth. More deeply buried sediments corresponded to a bituminous rank, supporting vitrinite reflectance data reported in Titheridge (1977), which places these in the oil window. Although in the southern region of the Pakawau Sub-basin kitchen areas have been structurally inverted and are no longer active kitchens (Smith et al., 2014) there is potential for more northern expressions of the North Cape Formation to represent source kitchens, supported by the sedimentological character of the outcropping units in this study. The implication is that the North Cape Formation may represent a petroleum system which contains both a viable hydrocarbon reservoir and local source rock units within the same formation.

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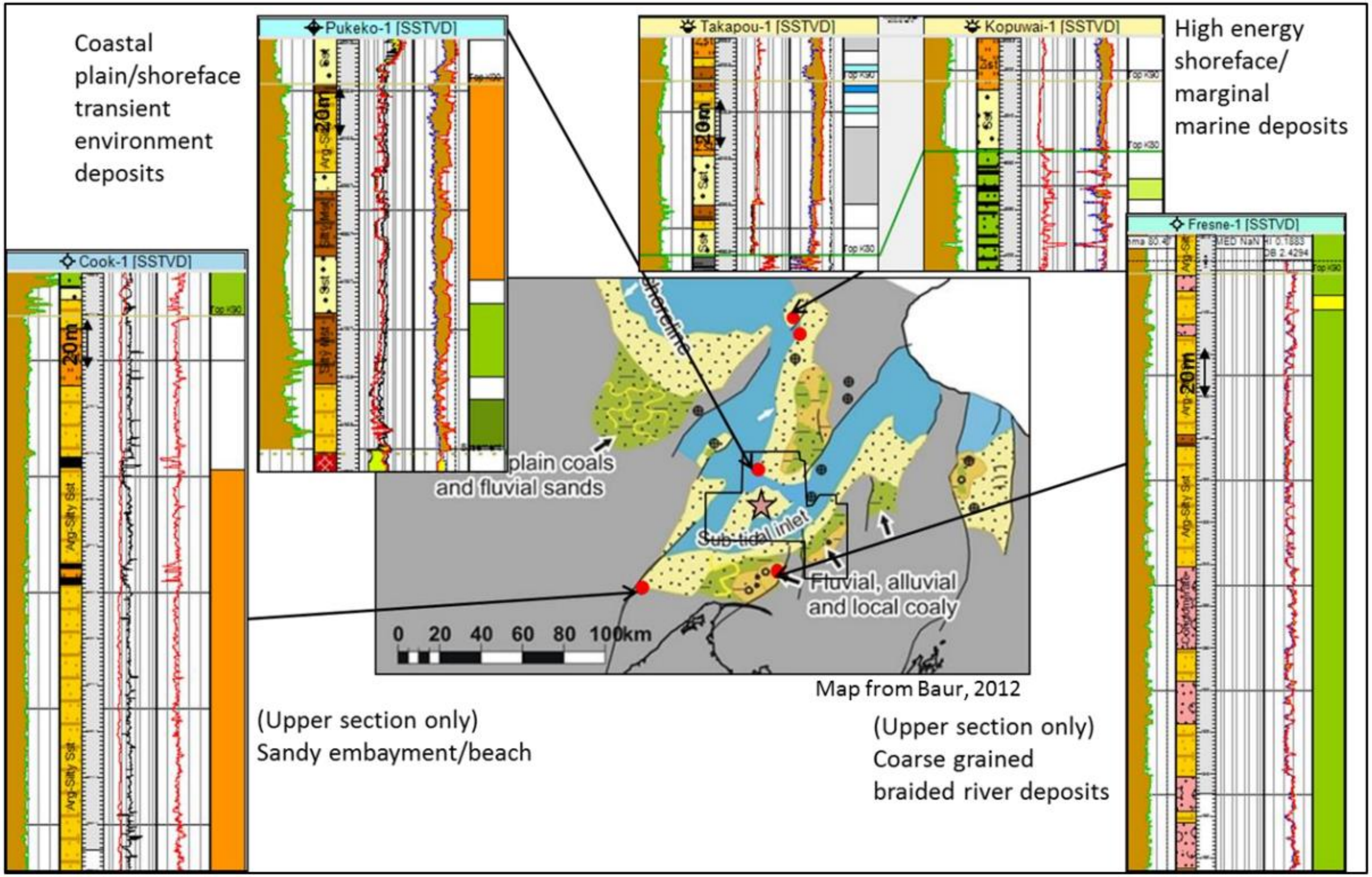

Figure 4.10 – Gross depositional environments for the North Cape Formation reservoirs in the central and southern Taranaki Basin (Smith et al., 2014)

4.4.2 – Analogous petrophysical characterisations of estuarine lithofacies.

Outcrop analyses provide important insight into the characterisation and evaluation of sub-surface oil bearing equivalent units. It is important to understand the small-scale facies changes in outcrop and measure the corresponding petrophysical properties to inform reservoir interpretation in offshore fields. Some possible analogues are presented below to which the North Cape Formation may have similarities.

The K3E stacked sandstones form the main gas-condensate reservoir of the onshore Kapuni Field (Figure 4.1) in the Taranaki Basin. These sands represent the base of the fluvial to estuarine sequences of the Eocene Mangahewa Formation (King et al., 2008; Higgs, 2009). The interbedded thin sandstones and siltstones, carbonaceous mud and Mangahewa coals in this formation are also a source for both oil and gas in the deeper areas of the Taranaki Basin (Robinson and King, 1988; King et al., 2008; Higgs, 2009). As with the North Cape Formation, lithofacies range from excellent reservoir sandstones through to highly carbonaceous very-fine sandstones, siltstones and coals which may represent hydrocarbon source rocks.

An integrated sedimentological and petrophysical investigation into the estuarine tide-dominated facies of the Miri Formation, Sarawak, within the Middle Miocene strata of the Miri oil field (Abieda et al., 2005) provides a useful analogue to the present study. The authors categorised the Miri Formation into two main lithofacies associations reflecting the paleo-depositional setting; 1) estuarine, tide-dominated and; 2) the shore-face-offshore transition, storm and wave-dominated facies associations.

Abieda et al. (2005) describe estuarine facies that are characterised by diagnostic tidal signatures, tidal dune cross-bedding with mud drapes and couplets, bi-directional cross-bedding, rhythmic stratifications, flaser and lenticular bedding. The shoreface-to-offshore transition wave-dominated facies generally displays vertically stacked wave- and storm-generated facies with considerable composite thickness (>12m). Six representative sandstone lithofacies were analysed for porosity and permeability, using water immersion under vacuum and gas permeability techniques, respectively. Porosities ranged from 13.5-29.7%, with permeabilities varying considerably from 3 up to 286 md. This study found the most important depositional control on porosity and permeability was grain size, with the best reservoirs channel and bar sandstones deposited in higher-energy depositional settings. Poorer quality reservoir properties were considered to be the result of finer grained sediments, high proportion of detrital sediments and higher presence of mud drapes that may have created permeability barriers at a facies scale. Additionally a high degree of bioturbation may reduce porosity and cause clay dispersion (Buatois et al., 2003). This study is important to compare with the results of the measured lithofacies in this study, showing that permeabilities can vary considerably with grain size.

The Lower Pennsylvanian Morrow Sandstone in southwest Kansas represents a complex of oil and gas reservoirs in a wide variety of depositional environments, from delta front to shore face and estuarine valley fill sandstones encased in offshore and estuarine mudstones. Byrnes et al. (2001) report that helium porosity values for the Morrow sandstone range between 0-22% and air permeability measurements range from 0.0001 md to 150mD. The fluvial and upper estuarine channel facies exhibit maximum porosity and permeability, moderate reservoir quality is reported restricted tidal flat and estuary mouth deposits, while non-marine paleosols, shelf deposits and lower estuary mudstones were considered non-reservoirs. Air permeability measurements were highest in fluvial and upper estuary channel sandstones, and coarse-grained sandstones exhibited higher permeability with given porosity than cleaner fine-grained sandstones. It is important to note that the fluvial and estuarine channel sandstone facies exhibit an order of magnitude greater permeability for any given porosity than the other measured facies. As with the Miri Formation (Abieda et al., 2005) the presence of mud drapes in the estuarine tidal and marine facies reduced permeability considerably.

The examples described above support the interpretation of the bar and channel sandstones of the Delta Front Lithofacies Association (DF) and Delta Plain Lithofacies Association (DP) of this study representing the best quality reservoir sandstones in the fluvio-estuarine sequences of the North Cape Formation. Additionally, the role of grain size in controlling the relationships between porosity and permeability is important for this study. The reduction in overall grain sizes from the conglomerates to medium sandstones in the northeast of the field area to the fine grained sandstones that dominate the west and southern outcrops of the North Cape Formation. Additionally, the better sorting of higher energy depositional settings that are more likely to yield better quality reservoir rocks highlight the lithofacies in closer proximity to distributary channels, for example the northern bay head gravelly delta and secondary distributary systems in the south which further reiterate the significance of the lithofacies of the Delta Front Association (DF). As described in the Miri Formation bioturbated, very-fine sandstones and siltstone lithofacies are among the poorest potential reservoirs (Abieda et al., 2005), and the same is concluded in the North Cape Formation. The bioturbated carbonaceous siltstone lithofacies **(Zb)** of this study records low porosity at 8% (Φv) and averages 4mD, where it is likely that both the lower grain size and the bioturbation reduces porosity and restricts fluid flow.

4.5 – Conclusion

Petrophysical properties of the assessed lithofacies of the North Cape Formation in the study area show good promise as potential reservoirs, with hydrocarbon accumulations likely associated with cross-bedded **(Sxt)** and wavy bedded **(Sw)** sandstones of the Delta Front Lithofacies Association (DF) and the Delta Plain Lithofacies Association (DP). Potential reservoirs may also occur in the heterolithic interbedded sandstone **(Hl)** units which also have good porosity and moderate permeability values. Better reservoir potential is closely related to grain size, where generally the coarser grained lithofacies occur in the northeastern region of the study area and have the highest porosity (both Φv and Φc) and permeability readings. Additionally, despite being well sorted the effects of cementation and diagenesis in the finer grained sandstones of the Delta Plain Lithofacies Association (DP) of the western outcrops resulted in reduced porosity, which is expected to also reduce permeability. Poorer quality reservoirs are present in the very fine to fine grained carbonaceous **(CS)** and planar laminated **(Sp)** sandstone lithofacies, with non-reservoirs in the bioturbated carbonaceous siltstone **(Zb)** lithofacies. Although measurements of petrophysical properties of the local conglomerate **(G)** lithofacies are limited, it is expected these will represent good quality reservoirs, particularly those with lower tidal influence and lower incidence of potential mud drapes creating flow baffles. Similar tide-dominated, fluvial and estuarine channel and bar lithofacies represent the best reservoir sandstones in analogous petroleum systems, while deeper marine and bioturbated fine grained units like those observed in the Sub-tidal Lithofacies Association (A3)in this study are poor or non-reservoir quality.

A number of lithofacies present in the North Cape Formation are rich in organic material with local coal lithofacies present throughout the study area providing evidence for potential disseminated local hydrocarbon sources. The North Cape Formation may therefore represent a unique petroleum system, containing both viable hydrocarbon reservoir and local source rock units.

Chapter 5 – Summary

5.1 – Summary

The Late Cretaceous North Cape Formation in its onshore expressions within the Pakawau Sub-basin shows distinct lateral variability in lithofacies, which has implications for paleogeography, depositional processes and its potential as a productive petroleum reservoir interval. The North Cape Formation is interpreted as a fluvio-estuarine unit dominated by medium sandstone and conglomerate lithofacies in the northeast, fine sandstone lithofacies in the west and south and heterolithic very fine to fine grained sandstones and siltstone in the central regions of the study area. Sedimentological analysis undertaken in this thesis has recognised ten distinctive lithofacies in the study area, which can be combined to represent three broader scale Lithofacies Associations, namely;

DP) Delta Plain, distributary channel environment - comprising sandy, fluvially dominated sediments with local floodplain deposition. Constituent conglomerate **(G)**, crossbedded sandstone **(Sxt, Sxp)** wavy bedded sandstone **(Sw)**, planar laminated sandstone **(Sp)** , carbonaceous sandstone **(CS)** and coal **(C)** lithofacies (Chapter 2).

DF) Tidally influenced Delta Front environment - comprising heterolithic, mixed fluvial and tidal processes. Recognised by crossbedded sandstone **(Sxt, Sxp),** wavy bedded sandstone **(Sw)** planar laminated sandstone **(Sp)** and heterolithic sandstone **(Hl and DHl)**, with rare conglomerate **(G)** lithofacies (Chapter 2).

ST) Sub-tidal environment - dominated by tidal processes, with little to no fluvial influence. Recognised by wavy bedded sandstone **(Sw)** planar laminated sandstone **(Sp),** heterolithic sandstone **(Hl and DHl)** and marine influenced carbonaceous siltstone **(Zb)** and silty coal **(CZ)** lithofacies (Chapter 2).

The variability in lithofacies and Lithofacies Associations has been used to characterise the paleodepositional environments within the study area. Interpretations suggest the North Cape Formation was deposited in a sandy, tide-dominated estuary which contained a local bayhead fan delta in the northeast, smaller scale tidal distributary channels throughout the field area and at least some partially sheltered tidal embayments with local salt marshes.

The central portion of the study area is characterised by the Sub-tidal Lithofacies Association (ST), where lithofacies record transitions from sub-tidal to tidal deposition in a lagoonal, estuarine environment with local salt marshes. The northern and southern regions of the study area are characterised by the tidally influenced Delta Front Lithofacies Association (DF), with the scale of distributary channels varying laterally. The northeast study arearecords deposition related to a bayhead fan delta environment which switched between fluvial and tidally dominated processes, while in the southern region it is assumed a secondary distributary channel system was present, and was being reworked and overprinted by tidal processes. The western coastline of the study area is characterised by fluvial dominated deposition where lithofacies record the switch from tidally influenced Delta Front deposition Association (DF) to Delta Plain Lithofacies Association (DP). These successions suggest that tidal influence became considerably less important during the deposition of the uppermost successions of the North Cape Formation.

Overall the depositional setting has been shaped by tidal processes and by sand dominated deposits, and to a lesser extent, by wave-generated deposition. This suggests there was no significant sand barrier at the estuary mouth during the deposition of the North Cape Formation. The reconstruction of the paleodepositional environments and geometry of the estuarine setting of the North Cape Formation has been aided by comparisons with modern and ancient tidally dominated estuary settings. The sedimentary successions within the study area record transitions from fluvial to tidal dominated deposition. The vertical and lateral lithofacies changes are similar to those recorded in the macrotidal Cobequid Bay – Salmon River Estuary (Bay of Fundy) (Dalrymple et al., 1990) with bar-channel deposits, upper-flow regime sands flats capped by muds and salt marsh sediments observed in the transition from Delta Front Lithofacies Association (DF) to Sub-tidal Lithofacies Association (ST). Additionally, the cyclic alternations between sub-tidal and supra-tidal deposition noticeable within the Sub-tidal Lithofacies Association (ST) may reflect localised transgressive and regressive packages, in response to sea-level fluctuations similar to the Chimney Rock Tongue, Upper Cretaceous-Campanian in the Western Interior Basin, Utah, USA (Plink-Björklund, 2008).

Petroleum Potential

The North Cape Formation shows good quality hydrocarbon reservoirs associated with crossbedded **(Sxt and Sxp)** and wavy bedded **(Sw)** sandstones off the Delta Front Lithofacies Association (DF) and the Delta Plain Lithofacies Association (DP). Porosity and permeability values indicate good potential reservoirs may also occur in the heterolithic interbedded sandstone **(Hl)** lithofacies of the Sub-tidal Lithofacies Association (ST). Weimer et al. (1982) describe the difference in scale and role of channels within the tidal flat environment to produce reservoir sandstones. Tidal channels are large and high-energy and typically produce reservoir sandstones, while smaller scale distributary channel patterns occur on tidal flats and tidal creeks, which because of shallow depths and low energy produce non-reservoir rocks and typically are thin, poorly sorted, silty and clayey sandstone. Although there are a number of small tidal creeks interpreted to cut the lithofacies of the Sub-tidal

Association (ST) the high net:gross ratio of the North Cape Formation and general lack of muds and clays in the field area is expected to increase the reservoir potential of the sandstones in these tidal environments.

In general, the North Cape Formation has better reservoir potential elated to grain size, where on average the coarser grained lithofacies that characterise the northeastern region of the study area have the highest porosity (both Φv and Φc) and permeability readings. Overall, the lithofacies are relatively well sorted, but the localities which record the best sorted deposits correspond to the better potential reservoir sandstones. The effects of diagenesis and cementation are however, important to consider when characterising the relative reservoir potential of the sandstone lithofacies in the North Cape Formation, where despite good overall sorting in the Oyster Point Delta Plain Lithofacies Association porosity and permeability were lower on average than equivalent units along the eastern coastline of the field area.

The North Cape Formation contains lithofacies that are locally rich in organic material with local coal lithofacies present throughout the study area. These lithofacies provide potential stratigraphically discrete hydrocarbon source rocks.

This work suggests that future exploration within the North Cape Formation may regard the formation as both a potential reservoir and source rock interval.

5.2 – Relevance

Global:

Generally, transgressive deposits are highly variable in thickness and the lithofacies that comprise them but can be texturally and compositionally mature making them excellent oil/gas reservoirs (Aschoff et al., 2016). Estuarine deposits are particularly important as they sequester and re-sort sandy deposits and tend to have a higher preservation potential due to their positions within flooded valley environments, resulting in good reservoir potential (Dalrymple et al., 1992; Aschoff et al., 2016).

The Northern Alberta Oil Sands are the largest in the world, covering a surface area of more than 140,200km2. The lower Cretaceous McMurray Formation is the oil bearing formation within the Athabasca oil sands area of Northern Alberta, Canada. This formation is renowned for its complex geological heterogeneity, with the majority of the heavy oil deposits contained within fluvio-estuarine channel point bar deposits (Hassanpour, 2009). The middle McMurray Formation contains the thickest successions and the highest quality reservoir sands. Regionally, the McMurray

Formation is comprised of fluvial, open estuarine channel complex deposits, with two distinct reservoir facies characterised:

- Large-scale cross-stratified sandstones, with clean sands, bedsets in excess of 50cm thickness and strong tidal indicators that indicate marine origin. This facies is considered outer estuary, proximal to estuary mouth;

- Heterogeneous deposits with notable primary dip, referred to as the inclined heterolithic stratification facies. These deposits are interpreted to form from lateral growth of active, large-scale point bars within meandering channels of tidally influenced rivers

The distribution of these oil sand resources is directly related to reservoir heterogeneity therefore it is has been crucial for researchers to understand the lithofacies and their relative reservoir potential (Langenberg et al., 2001; Pengfei et al., 2013). Through the assessment of core description data, good understanding of regional geology combined with geophysical data the authors were able to establish the relative reservoir potential of the lithofacies present within the middle McMurray Formation (table 5.1) (Pengfei et al., 2013) which reduces the complications for economic development of the oil sands (Langenberg et al., 2001).

Table 5.1 – Classification of the facies groups within the Middle McMurray Formation, Northern Alberta, Canada. Modified after Pengfei et al. (2013)

Member	Facies group	Facies	Brief description	Depositional environment	Bitumen content
Middle McMurray Formation	Reservoir facies	Estuarine channel sand	Fine-medium grained, well sorted sand with low-angle cross beddings	Estuarine	>6%
		Tidal channel sand	Dominantly fine grained, well sorted sand with low-angle cross beddings, and few burrows	Tidal channel	>6%
	Possible reservoir facies	Silt/sand flat	Silt/very fine-fine grained sand with interbedded/ interlaminated mud, moderately bioturbated	Tidal flat	5%-8%
		Channel breccia	Fine-medium grained sand with greater than 10% mud breccia, chaotic	Tidal/estuarine channel	6%-10%
	Non-reservoir facies	Mud flat	Thick mud with interlaminated very fine-fine grained sand/silt	Tidal flat	<4%
		Mixed flat	Interbedded/interlaminated very fine-fine grained sand and mud, intensively bioturbated		
		Abandoned channel mud	Thick mud with interbedded thin fine grained sand		
		Estuarine channel sand	Fine-medium grained, well sorted sand with low-angle cross beddings	Estuarine channel	<6%
		Tidal channel sand	Dominantly fine grained, well sorted sand with low-angle cross beddings, and few burrows	Tidal channel	<6%

As discussed in Chapter 3 the sedimentary successions described by Aschoff et al. (2016) in Book Cliffs, Utah represent deposition in a tidally dominated bayhead delta. The authors acknowledge that although the reservoir characteristics of bayhead delta deposits are not well known, their typical geometries and the character of lithofacies that comprise them suggest that multiple bay head delta deposits may fill a single paleo valley system. Additionally, the strong effect of tidal overprinting in these deposits is likely to result in reservoir heterogeneity with flow baffles associated with mud drapes. Tidal overprinting in the bayhead delta deposits of the Book Cliffs results in the obliteration of the original fluvial generated fabric. It is expected that bayhead delta reservoir deposits with considerable tidal influence, like the North Cape Formation, would be reorganised into lobe- and ribbon-shaped compartments of heterogeneous sandstones with numerous conglomerates and tidal mud drapes baffles within the units. These reservoirs as a result are likely complex, but would be relatively easy to image in seismic due to their position in a paleo valley (Aschoff et al., 2016).

Local:

The economic importance of constraining reservoir geometries and assessing petroleum potential means that high-detailed, local scale lithofacies analyses like those presented in this study are crucial in constraining traditional, broader-scale exploration techniques. The Eocene shallow marine sandstone reservoirs of the Taranaki Basin have been well described and depositional facies are interpreted as being one of the principal controls on reservoir quality. Proven reservoirs are largely attributed to quartz rich, coarse grained channel-fill and upper shoreface/shoreline sandstones (Higgs et al., 2012; Higgs et al., 2017). The authors describe the lithofacies that exhibit the best reservoir properties as being those that have not experienced significant cementation, compaction and burial. The Oyster Point outcrops of the North Cape Formation appear to have undergone more considerable diagenesis and cementation and show the poorest reservoir properties. Previous analyses of the reservoir potential of the Late Cretaceous rocks in the southern Taranaki Basin have identified good potential reservoir targets in both the high energy channel and alluvial fan facies of the Rakopi Formation and channel fill and shoreface lithofacies of the North Cape Formation (Browne et al., 2008; Higgs et al., 2010). A summary of available well and outcrop analyses presented in Higgs et al. (2010) show that more extensive Late Cretaceous sandstone reservoirs exist in the shoreline and shallow marine lithofacies of North Cape Formation in the northwest Nelson region than previously predicted. The analyses presented in this study support these earlier interpretations, with the best quality reservoirs assigned to the Delta Front and Delta Plain Lithofacies Associations shoreface and channel sandstones.

The distribution and lateral variability of the lithofacies in the North Cape Formation, in this study, provide important information for the characterisation of paleodepositional environments and reservoir geometries which can be applied to analogous settings and aid offshore interpretation within the southern Taranaki Basin. There are few wells (Fresne-1, Cape Farewell-1, Cook-1) (figure 1.1) and no seismic collected near the Late Cretaceous outcrop in the Pakawau Sub-basin so the high-detailed local interpretation presented in this research may provide missing data that could guide placement of any future exploration targets. Additionally, the high-detailed and localised lithofacies analyses in this research will enable better constraint of the paleodepositional environments during the Late Cretaceous and ultimately provide a framework for the characterisation of similar depositional settings.

5.3 - Conclusion

The outcropping North Cape Formation in the study area is interpreted to have been deposited in an open estuarine setting which contained a combination of sub-tidal, delta front and delta plain associated depositional settings. Vertical and lateral lithofacies patterns reveal unique paleodepositional environments with deposits that range from high energy, gravelly distributary channels to salt marsh and fresh water peat swamps. Spatially, the North Cape Formation is interpreted as having a local bayhead fan delta in the northeast, smaller scale tidal distributary channels throughout its expression in the study area and partially sheltered tidal embayments with local salt marshes in the central regions.

Lithofacies analyses combined with petrophysical analyses have confirmed that the North Cape Formation contains both viable hydrocarbon reservoirs and potential source units and can therefore be considered a unique petroleum system. The interpretations presented in this study are considered important to better understanding the paleodepositional settings of the Late Cretaceous North Cape Formation and may be useful for guiding future exploration of petroleum systems of the southern Taranaki Basin. Additionally, it is hoped this research may act as a framework for characterising similar ancient environments.

References:

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Appendix 1: Petrophysical Data.

1.1 – Core data

Core Data Summary Table								
		GPS (WGS 1984)					Core	
Location	Sample code:	S	E	Lithofacies	Grain Size (avg)	Drilling direction	Porosity (Φc) (%)	Permeability (kc) (mD)
Pecks Point North	CPP01	40.56879	172.62854	Hl	Fine	Parallel	35.66	64.54
	CPP02			Sxt	Medium	Parallel	36.00	280.52
	CPP03.1	40.56897	172.62694	Sw	Medium	Parallel	33.75	545.05
	CPP03.2			Sw	Medium	Parallel	35.35	163.98
	CPP08			Sw	Medium	Parallel	36.38	290.66
	CPP10.1			Sw	Medium	Parallel	36.50	119.42
	CPP10.2			Sxt	Medium	Parallel	35.00	19.93
	CPP11.1	40.56885	172.62672	Sxt	Medium	Oblique	35.10	294.55
	CPP11.2			Sxt	Medium	Oblique	34.58	255.55
	CPP11.3			Sxt	Medium	Parallel	35.58	173.26
	CPP11.4			Sxt	Medium	Parallel	33.29	49.94
	CPP11.5			Sxt	Medium	Perpendicular	35.86	135.61
	CPP11.6			Sxt	Medium	Perpendicular	35.48	49.21
	CPP20			Sxt	Medium	Parallel	35.12	97.33
Pecks Point CGL	CPCGL01			Sw	Coarse	Perpendicular	33.47	343.94
	CPCGL01.1			CS	Fine	Perpendicular	30.51	345.70
Wairoa River North	CWRN01	40.60853	172.57858	Hl	Very fine - fine	Parallel	23.27	0.81
	CWRN05			Hl	Very fine - fine	Perpendicular	24.57	0.96
	CWRN10			Hl	Very fine - fine	Parallel	26.48	0.33
	CWRN13	40.60694	172.57803	Sxt	Coarse upper	Parallel	35.33	538.68
	CWRN14			Sxt	Medium upper	Parallel	32.93	123.12
	CWRN19.1			Sw	Fine	Parallel	35.67	120.64
	CWRN19.2			Sw	Fine	Parallel	37.82	41.58
	CWRN23.1			Sw	Fine	Perpendicular	27.76	38.51
	CWRN23.2			Sw	Fine	Perpendicular	35.04	42.88
	CWRN26			Sw	Fine upper	Perpendicular	34.79	14.67
Oyster Point	COP03	40.57042	172.59988	CS	Very fine - fine	Parallel	18.25	
	COP04			CS	Very fine - fine	Parallel	18.29	
	COP12	40.57107	172.59874	CS	Very fine - fine	Perpendicular	20.27	
	COP13			CS	Very fine - fine	Perpendicular	21.17	
	COP15			Hl	Fine-medium	Parallel	18.12	
	COP16			Hl	Fine-medium	Parallel	19.42	
	COP68			Hl	Fine-medium	Perpendicular	17.61	
	COP69			Hl	Fine-medium	Perpendicular	22.61	
	COP32			Hl	Silt-very fine	Perpendicular	17.06	
	COP38			Hl	Silt-very fine	Perpendicular	18.00	
	COP47			Hl	Silt-very fine	Parallel	18.83	
	COP50			Hl	Silt-very fine	Parallel	18.59	
	COP77			Sxt	Medium	Parallel	21.03	
	COP79			Sxt	Medium	Parallel	20.02	

1.1 – *In situ* permeability data

In situ permeability data

CS			HI			HI			HI		
Outcrop	(mD)	Notes:	Outcrop	(mD)	Notes:	Outcrop	(mD)	Notes:	Outcrop	(mD)	Notes:
PPN	6.000	Fss	PPN	1.227	Silt/vfss	OYP	76.700	Vf/Fss	WRS	1.945	Rippled f/vfss
PPN	60.000	Fss	PPN	16.128	Silt/vfss	OYP	2.000	Vf/Fss	WRS	0.145	Rippled f/vfss
PPN	18.000	Fss	PPN	26.083	Silt/vfss	OYP	56.700	Vf/Fss	WRS	2.367	Rippled f/vfss
ICN	7.129	Vfss	ICN	48.468	Silt/vfss	OYP	2.900	Vf/Fss	WRS	0.963	Rippled f/vfss
ICN	67.443	Vfss	ICN	25.662	Silt/vfss	OYP	15.400	Vf/Fss	WRS	70.936	Rippled f/vfss
ICN	62.822	Vfss	ICN	2.061	Silt/vfss	OYP	2.100	Vf/Fss	WRS	22.272	Rippled f/vfss
OYP	92.828	Vfss	MS	122.721	Fss	OYP	40.600	Vf/Fss	WRS	17.311	Rippled f/vfss
OYP	0.079	Vfss	MS	170.857	Fss	OYP	12.800	Vf/Fss	WRS	31.678	Rippled f/vfss
OYP	41.106	Vfss	MS	109.976	Fss	OYP	1.800	Vf/Fss	WRS	49.893	Rippled f/vfss
Zb			MS	54.405	Fss	OYP	17.300	Vf/Fss	WRS	73.509	Rippled f/vfss
Outcrop	(mD)	Notes:	MS	252.815	Fss	OYP	3.200	Vf/Fss	WRS	21.364	Rippled f/vfss
MCK	6.725	Vfss	MS	125.583	Fss	OYP	19.300	Vf/Fss	WRS	4.809	Rippled f/vfss
MCK	8.718	Vfss	MS	69.639	Fss	OYP	1.500	Vf/Fss	WRS	18.095	Rippled f/vfss
WRN	0.021	Vfss	MCK	8.149	Fluid escape structures	OYP	9.300	Vf/Fss	WRS	19.192	Rippled f/vfss
WRN	4.809	Vfss	MCK	53.942	Fluid escape structures	OYP	3.500	Vf/Fss	WRS	6.563	Rippled f/vfss
WRN	7.475	Vfss	MCK	23.340	Fluid escape structures	OYP	26.616	Vf/Fss	WRS	2.778	Rippled f/vfss
WRN	2.816	Vfss	MCK	90.185	ripple lam	WRN	1.994	Vfss	WRS	2.848	Rippled f/vfss
WRS	0.110	Silt/vfss	MCK	364.109	ripple lam	WRN	0.222	Vfss	WRS	15.946	Rippled f/vfss
WRS	3.372	Silt/vfss	MCK	64.086	ripple lam	WRN	0.121	Vfss	WRS	85.204	Silt dom
WRS	5.096	Silt/vfss	MCK	16.968	ripple lam	WRN	0.063	Vfss	WRS	175.404	Silt dom
WRS	0.989	Silt/vfss	MCK	15.183	ripple lam	WRN	1.892	Vfss	WRS	25.507	Silt dom
WRS	14.692	Silt/vfss	MCK	40.084	ripple lam	WRN	11.227	Vfss	WRS	14.542	Silt dom
WRS	0.847	Silt/vfss	MCK	84.913	ripple lam	WRN	10.098	Vfss	WRS	22.323	Silt dom
WRS	0.140	Silt/vfss	MCK	6.167	ripple lam	WRN	0.521	Vfss	WRS	58.488	Silt dom
HI			OYP	19.381	silt/vfss intb	WRN	0.913	Vfss	WRS	106.371	Vfss

Outcrop	(mD)	Notes:	OYP	8.606	convolute beds	WRN	7.050	Vfss	WRS	86.070	Vfss
PPN	10.820	Silt/vfss	OYP	0.642	convolute beds	WRN	21.410	Vfss	WRS	97.737	Vfss
PPN	4.291	Silt/vfss	OYP	2.817	convolute beds	WRS	6.747	Rippled f/vfss	WRS	44.472	Vfss
PPN	0.743	Silt/vfss	OYP	1.840	silt/vfss intb	WRS	1.339	Rippled f/vfss	WRS	82.459	Vfss
			OYP	3.400	Vf/Fss	WRS	7.342	Rippled f/vfss	WRS	124.321	Vfss
Hl			**Sp**			**Sw**			**Sxt**		
Outcrop	(mD)	Notes:	Outcrop	(mD)	Notes:	Outcrop	(mD)	Notes:	Outcrop	(mD)	Notes:
WRS	30.894	Vfss	WRS	70.936	Rippled f/vfss	PPN	7.165	Fuss	PPN	124.068	Css
WRS	13.932	Vfss	WRS	22.272	Rippled f/vfss	ICN	265.959	Mss	PPN	211.029	Css
WRS	1.066	Vfss	WRS	17.311	Rippled f/vfss	ICN	276.519	Mss	PPN	372.637	Css
Sp			WRS	31.678	Rippled f/vfss	ICN	72.562	Mss	PPN	2.978	Fss
Outcrop	(mD)	Notes:	WRS	49.893	Rippled f/vfss	ICN	150.378	Mss	PPN	17.209	Fss
MCK	16.326	Next to channel	WRS	73.509	Rippled f/vfss	ICN	165.932	Mss	PPN	3.058	Fss
MCK	3.306	Next to channel	WRS	21.364	Rippled f/vfss	MS	277.151	VCLss	PPN	10.721	Css
MCK	30.979	Fss	WRS	34.414	fss	MS	354.911	VCLss	PPN	92.353	Css
MCK	21.836	Fss	WRS	0.287	fss	MS	99.229	VCLss	PPN	356.956	Css
MCK	74.796	Fss	WRS	5.132	fss	MS	127.995	VCLss	PPN	143.027	Css
MCK	45.972	Fss	WRS	0.045	fss	MS	195.219	VCLss	PPN	20.777	Css
MCK	19.014	Fss	WRS	0.260	fss	MS	439.459	VCLss	PPN	89.794	Mss
MCK	22.547	Fss	WRS	1.532	fss	MS	357.949	VCLss	PPN	43.618	Mss
OYP	0.256	MLss	WRS	183.060	fss	MS	125.472	VCLss	PPN	287.137	Mss
OYP	1.073	MLss	WRS	7.579	fss	MS	898.527	VCLss	PPN	227.196	Mss
OYP	3.354	MLss	WRS	1.356	fss	MS	297.936	VCLss	PPN	190.765	Mss
OYP	2.280	Fss	**Sw**			MS	672.077	VCLss	PPN	634.675	Mss
OYP	22.893	Fss	Outcrop	(mD)	Notes:	MS	23.343	Css	PPN	521.258	Mss
OYP	2.552	Fss	PPN	89.950	Mss	MCK	5.125	MLss	PPN	544.145	Mss
WRN	19.072	Fss	PPN	29.065	Mss	MCK	57.266	MLss	PPN	932.529	Mss
WRN	9.491	Fss	PPN	41.905	Mss	WRN	54.608	Muss	PPN	286.795	Mss
WRN	12.750	Fss	PPN	7.073	Mss	WRN	7.441	Muss	ICN	87.016	Muss

WRS	1.771	Fss
WRS	6.747	Rippled f/vfss
WRS	1.339	Rippled f/vfss
WRS	7.342	Rippled f/vfss
WRS	1.945	Rippled f/vfss
WRS	0.145	Rippled f/vfss
WRS	2.367	Rippled f/vfss
WRS	0.963	Rippled f/vfss

Sxp		
Outcrop	(mD)	Notes:
PPN	43.728	VCss
PPN	495.656	VCss
PPN	17.239	VCss
PPN	9.205	Css
PPN	38.739	Css
PPN	170.197	Css

G		
Outcrop	(mD)	Notes:
PPN	602.469	Css matrix
PPN	504.751	Css matrix
PPN	371.850	Css matrix
PPN	436.685	Css matrix
PPN	235.584	Css matrix
PPN	278.374	Css matrix
PPN	227.772	Css matrix
PPN	115.090	Css matrix
PPN	325.937	Css matrix
PPN	563.582	Css matrix
PPN	930.044	VCss

PPN	20.551	Mss
PPN	84.993	Mss
PPN	38.971	Mss
PPN	31.237	Mss
PPN	13.530	Mss
PPN	11.876	Mss
PPN	35.235	Fuss
PPN	22.429	Fuss

WRN	72.593	Muss
WRN	22.777	Muss
WRN	3.474	Fss
WRN	7.129	Fss

Sxt		
Outcrop	(mD)	Notes:
PPN	171.620	Css
PPN	150.001	Css

ICN	108.776	Muss
ICN	86.155	Muss
ICN	257.762	Muss
ICN	281.828	Muss
ICN	86.582	Muss
ICN	41.148	Muss
ICN	96.208	Muss
ICN	273.490	Css

Code	Outcrop
PPN	Pecks Point North
ICN	Island Creek
MCK	Muddy Creek
WRN	Wairoa River North
WRS	Wairoa River South
OYP	Oyster Point
MS	Mangarakau Swamp

Lithofacies	Permeability (in situ) (mD)		
	Range	Average	Count (=n)
CS	0.08 - 92.83	39.490	9
Zb	0.02 - 14.7	4.293	13
Hl	0.06 - 364.1	36.868	96
Sp	0.05 - 183.1	20.774	41
Sw	3.47 - 898.5	143.816	38
Sxt	2.98 - 932.5	227.115	51
Sxp	9.21 - 496.7	129.127	6
G	115.1 - 930	417.467	11

1.2 – Thin section (visual porosity) data

SAMPLES							VISUAL POROSITY SAMPLES					
Location	Sample No:	Grain Size:	Lithofacies	Description	GPS (WGS 1984)		Porosity (Quantitative)			step length (mm)	Porosity ΦV (%)	Notes
					S	E	Grain	Void	Count			
PPN	1.1	VcUss	Sxp	Granular/VsUss with Tabular xbeds			166	34	200	1	17.0	
PPN	1.2	VcLss	Sxt	CU/VcLss w some granules trough xbeds			108	92	200	1	46.0	
PPN	2.1	MLss	Sxt	MLss w trough xbeds	40.50859	172.62889	144	56	200	1	28.0	(roughly equiv location to CPP1-2 - though cores were in intb, more fss)
PPN	2.2	Czst	Hl	Zst/Vfss interbeds with MLss lenses	40.56883	172.62837						
PPN	2.3	Cuss	Sw	MU-Cuss w some granules (massive)			121	79	205	1	38.5	
PPN	2.4	Muss	Sxt	Muss w trough xbeds	40.56896	172.62743	140	60	200	1	30.0	
PPN	3.1	CZst	Hl	Interbedded CZst/VfLss								
PPN	3.2	VCLss	Sw	VcLss with intbds of silt and vfss								
PPN	3.3	CUss	Sw	Massive Cuss with some granules	40.56866	172.62817						
PPN	3.4	VCLss	Sxt	VCLss with granules and trough xbeds	40.56866	172.6285						
PPN	3.5	VfLss	Hl	Interbedded Vfss/Zst with wave ripples	40.56871	172.62801						
PPN	3.6	Cuss	Sxp	Tabular xbedded Cuss			175	25	200	1	12.5	
PPN	3.7	VfLss	Hl	Interbedded Vfss/Zst			140	66	206	1	32.0	
PPCGL	1.1	Muss	Sw	Muss w silt smiles	40.57292	172.63373						
PPCGL	1.2	Cuss	G	Cuss CGL (Massive)	40.57273	172.63385	162	38	201	1	18.9	
PPCGL	3.1	Fuss	Sp	Plam FU/MLss	40.57792	172.63318						
PPCGL	2.1	CLss	Sxt	CLss w trough xbeds	40.57151	172.63223	144	56	200	1	28.0	
PPCGL	2.2	Fuss	Sw	Massive Fuss	40.57151	172.63223						
MCK	1.1	Fuss	Hl	Slightly wavy intbd Fuss (Zst-Muss) w ripples	40.58892	172.61871						

MCK	1.2	FLss	Sp	FLss (planar bedded) w fluid escape structures	40.58881	172.6189						(roughly equiv to CMC1-2)
MCK	1.3	MLss	Sp	Plam Fuss/MLss	40.8886	172.6192	152	48	200	1	24.0	
MCK	1.4	FLss	Sp	Plam FL/VfUss			139	61	200	0.5	30.5	
WRN	4.1	FLss	Sw	Fss wavy bedded	40.60694	172.57803	132	68	200	1	34.0	(Same as CWRN19-22)
WRN	4.2	Muss	Sxt	Muss -CLss w trough xbeds			136	64	200	1	32.0	(Same as CWRN13)
WRS	1.1	CZst	DHl	Wavy interbedded Vfss and Silt (w burrows)	40.60844	172.5752						
WRS	1.2	Fuss	Sw	Wavy bedded Fuss	40.60868	172.57512	151	49	200	1	24.5	
WRS	1.3	Coal	CZ	Coal	40.60886	172.57533						
WRS	1.4	Carb Zst	Zb	Carbonaceous Mud	40.60886	172.57533	130	70	200	1	35.0	
WRS	1.5	VfLss	Hl	Wavy interbedded Vfss and Silt (Similar unit to dino print section)								
WRS	1.6	FUss	Hl	Plam-wavy bedded Fuss with MLss lenses and silt intbds	40.60957	172.57512						
WRS	1.7	Carb Zst	Zb	Carb. Mud/Zst with organic lenses (Overlyinh intbds of Vfss)	40.60965	172.57535	184	16	200	0.5	8.0	
WRS	1.8	FUss	Sw	Wavy bedded FL/Fuss	40.60786	172.57556						
ICK	1.1	Muss	Sw	Wavy bedded Muss w rip ups and organics	40.6175	172.53503						
ICK	1.2	VfUss	Sw	VfUss w rip ups	40.61745	172.53511	154	46	200	1	23.0	
ICK	1.3	FLss	Hl	VfU/FLss w silt + some organics			142	59	201	0.5	29.4	
ICK	1.4	VfUss	Hl	VfUss w MLss intbds			152	48	200	0.5	24.0	
ICK	1.5	Muss	Sp	Plam MUss								
ICK	1.6	Fuss	Sxt	Fuss w trough xbeds and some wavy bedding			146	59	205	1	28.8	
SI	1.1	Fuss	Sp	Plam Fuss	40.61192	172.52278	145	55	200	1	27.5	
SI	1.2	Coal	C	Coal								

SI	1.3	Carb Zst	CS	Carb Zst/Mud							
SI	1.4	Carb Zst	CS	Same unit a sample 1.3 (whole)	40.61219	172.52231					
THR	1.1	Muss	Sxt	Muss w small/faint trough xbeds	40.61399	172.5135	143	57	200	1	28.5
THR	1.2	Fuss	CS	Fuss w coal at top and thin organic stringers throughout			154	50	204	1	24.5
THR	1.3	FLss	Sp	Plam Fss w silt and organics							
THR	1.4	Clss	SW	Slightly wavy bedded Clss			146	54	200	1	27.0
THR	1.5	FZst	Hl	V. Fine Zst bed (thin)			182	18	200	0.5	9.0
MS	1.1	CLss	Sw	CLss - poorly sorted			135	65	200	1	32.5
MS	2.1	VfUss	Hl	Interbedded VfU/FLss with CZst			168	32	200	1	16.0
MS	2.2	VCUss	Sxt	VcUss w rip ups and trough and small tabular xbeds			160	40	200	1	20.0
MS	2.3	VfUss	Sp	Vf/Zst plam (on top of convolute bedding w dino print- ? Bouma sequence)							
MS	2.4	FLss	Hl	Wavy bedded VfU/FLss (below coal layer)			164	36	200	1	18.0
MS	2.5	Coal	CZ	1st coal layer from Gregs Section							
MP	1.1	FLss	Hl	Wavyish Intb FLss w Zst (~10m into section)	40.58107	172.62776					
MP	1.2	MLss	Sw	Mss intbd w Fss ~13m up section	40.58105	172.62741					
MP	1.3	CLss	SW	Oganic rich Css at top of pebble horizon (~18m)							
MP	1.4	CLss	Sxt	Css w trough xbeds (26m)	40.58073	172.62653	174	26	200	1	13.0
MP	1.5	MLss	Sxt	MLss w trough xbeds (~28m)							
MP	1.6	Vfuss	Hl	Intbd Vfss-Zst w ripples (~32 up section)	40.58047	172.62614					
MP	1.7	Cuss	Sxp	Tabular xbedded Cuss (~31m up section)	40.58047	172.62614					

MP	1.8	VcLss	Sxt	Vcss w granules trough xbedded	40.58043	172.6257	161	39	200	1	19.5	
MP	1.9	FZst	Hl	Fzst/mud w Vf intbds and CLss lenses (~62m)	40.57969	172.6244	172	30	200	1	15.0	
OYP	1.1	MLss	Sw	MLss (from ~6m up Gregs section)								
OYP	1.2	VfLss	Hl	Vfuss w CZst (top of North Cape - Gregs Section)	40.57038	172.59875						
OYP	1.3	CLss	Sw	CLss w pebbles and organics			178	22	200	1	11.0	
OYP	1.4	Carb Zst	Cs	Carbonaceous CZst								
OYP	1.5	MLss	Cs	FU/MLss w organics and rootlets								
OYP	1.6	MLss	Sxt	Mss w organics and faint trough xbeds								
OYP	1.7	vfuss	Hl	Vfss w ripples			186	14	200	1	7.0	
OYP	1.8	vfuss	Sxt	VfUss w apparent trough xbeds (couldn't see personally)								
OYP	2.1	VfUss	CS	Vfss/Z intb (more s dom) iron nodules and organics common	40.57042	172.59988	192	13	205		6.3	equivalent to (COP0-5)
OYP	2.2	Fuss	Hl	Intb f/vf ss w lots of organics								equivalent to (COP5-77)
OYP	2.3	Muss	Sw	Muss w organics (more massive)	40.57111	172.59909						
OYP	2.4	Muss	Sxt	MUssTrough xbedded	4.57107	172.59874	152	48	200	1	24.0	(~29m up section) Equiv. to COP(78-)
OYP	2.5	MLss	Sw	Mlss w thin organic stringers	40.57074	172.599	141	60	201	1	29.9	~32m up section (at base of contact w carb silt)